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Evaluating Forest Stand Nutrient Status

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INTRODUCTION

This manual offers guidelines for evaluating forest stand and site nutrient status for silvicultural purposes. Forest fertilization is the only silvicultural practice explicitly considered, but some aspects of the guidelines may also be applied where estimation of nutrient status affects other silvicultural decisions, such as choosing among site preparation alternatives.

Two fertilization objectives are recognized: 1) growth stimulation, where operational fertilization is justified by the economic benefits of volume growth response; and 2) rehabilitation, where effective stand establishment or normal tree development may require relief from acute nutrient deficiency.

Preliminary assessments of sites and stands are discussed in the first chapter. Such assessments can provide sufficient information for the silviculturist to make tentative inferences about nutritional problems, or to decide whether more expensive sampling and laboratory analysis are justified.

The second chapter discusses the advantages and disadvantages of soil and foliar analyses for diagnosing nutritional problems. Guidelines for the collection, preparation, and laboratory analysis of soil and foliage samples are presented, and the interpretation of analytical results is discussed. In the third chapter, a computerized diagnostic program is introduced as an aid for the evaluation of foliage nutrient data.

This guide does not review all of the existing and rapidly evolving methods for evaluating stand or site nutrient status. Those suggested for routine silvicultural applications use cost-saving, simplifying assumptions, and though these may not always be justified for research purposes, some of the alternatives that yield more precise data have been rejected because the existing data interpretations are better developed for the less precise methods. While standardization of methods is desirable, facilitating comparisons of different stands or different sites, in the future it may become undesirable if it unduly retards adoption of newer, better methods. Because research to develop diagnostic interpretations of nutrient status is time-consuming and expensive, routine silvicultural applications rely on interpretations already in existence. Usually such applications must employ the same sampling criteria (and often the same analytical methods) used in the studies that developed the interpretations.

1 PRELIMINARY ASSESSMENT

1.1 Assessment Strategies

Sampling and analysis of foliage and soil to evaluate stand nutrient status can be expensive, and as such, are normally confined to those stands where they are clearly required for silvicultural decision-making. Forest fertilization prescriptions should be based on precise diagnosis of nutritional problems. Prescription of silvicultural treatments other than fertilization may require similar diagnostic precision but often may be based on less complete and less precise information.

A strategy for preliminary assessment of stands can help confine use of expensive methods to situations where they are most beneficial. Several silvicultural treatments other than fertilization influence stand nutrition, but while the choice among alternatives may be influenced by an inexpensive estimate of nutrient status, the potential gains in productivity may not justify more expensive evaluations. In the case of forest fertilization, inexpensive evaluations may suffice to disqualify some stands from consideration, with progressively more expensive criteria being used to disqualify the remaining unsuitable stands.

The criteria for inexpensive evaluations fall into three groups - stand, ecological, and management. Stand and management criteria include location, access, terrain, regional climate, species, stand age, tree size, and stocking. Such information may already be available to the forest manager. Ecological criteria, such as soil parent material, depth, texture, drainage, and organic matter content, and such limiting factors as insects and disease, may require special data collection. Visual symptoms of nutrient deficiencies can sometimes be identified in the field. By integrating all this preliminary information, forest managers can evaluate the prospects for gaining an economic growth response to fertilizer. The above criteria are discussed in the following sections of this chapter.

1.2 Location, Access, and Terrain

Location is primarily important to travelling and hauling time between the stands, potential fertilizer distribution points, camps, and log dumps. Increased travelling time reduces the economic rate of return on fertilization investments, and therefore, the most remote stands tend to have low priority when fertilization is being considered.

Access is a consideration for three reasons. First, it may affect feasibility of silvicultural treatments (e.g., spacing) which may be needed

to obtain an economic response to fertilization. Second, it is necessary for construction of the heliport or airstrip used as a fertilizer loading point for aerial application, and for ground transport of fertilizer to the aircraft loading point. Third, in stands fertilized long before rotation age, commercial thinning may be necessary to maximize returns. Thus, not only present access, but also the prospect of maintaining future access must often be considered.

Terrain may influence the application of fertilizers. For example, uniform application in steep or irregular terrain may be difficult with helicopters and virtually impossible with fixed-wing aircraft, and open water, such as lakes or streams, requires buffer zones where no fertilizer may be applied.

The total application area of an operational fertilization project should be sufficiently large for economic application. About 200 ha is a reasonable minimum, with the area separated into several - usually rectangular - blocks, for economic aerial application along parallel flight lines. For efficiency, such an area should be served by very few aircraft loading points, the location of which would be chosen to minimize flying time, as well as to take advantage of favourable terrain for construction.

1.3 Tree Species and Stand Age

The primary consideration in regard to tree species is whether a significant response to fertilizer treatments can be expected with a minimum of risk. At the present time, fertilizer trial results for species other than Douglas-fir, western hemlock, and lodgepole pine are few or nonexistent in the Pacific Northwest. In general, there is not sufficient evidence to justify operational application of growth-stimulating fertilizers to stands of Sitka spruce, white spruce, Engelmann spruce, subalpine fir, grand fir, amabilis (Pacific silver) fir, western redcedar, yellow-cedar, mountain hemlock, or western larch in British Columbia. The available evidence for western hemlock, lodgepole pine, and ponderosa pine suggests that growth responses are too marginal and/or too unpredictable to justify operational fertilization at the present time. Only coastal Douglas-fir has been shown frequently to give excellent responses to nitrogen fertilizer, although it is surmised that the response potential of interior Douglas-fir may be similar. As data accumulate from the many fertilizer trials now established in British Columbia, it may be possible to determine whether, under some site conditions at least, economic growth responses to fertilizers might be obtained in species other than coastal Douglas-fir; but until then, occurrence of these other species on a forest site might be used as a basis for disqualifying candidate sites.

Juvenile stands (i.e., those with incomplete crown closure) in the Pacific Northwest have seldom been considered suitable for fertilization, because fertilizer often tends to stimulate brush competition. Even where brush is not a problem, fertilization of such young stands with growth-stimulating fertilizers might be considered inappropriate, because there are few data to enable one to forecast the results. Recent research suggests that a number of growth anomalies may be caused by micronutrient deficiencies. In this case, fertilization may play a rehabilitative rather than stimulative role and treatments should be applied at as early an age as symptoms and deficiencies can be confidently diagnosed.

Managed stands about eight years before rotation age are likely to be suitable candidates for growth-stimulating fertilizer treatments. An eight-year period may be enough time to realize nearly all of the growth response usually resulting from fertilization, and be economically profitable. On sites where growth responses are relatively large, stands can be profitably fertilized somewhat earlier. Fertilization of stands much more than a decade before final harvest may be unprofitable unless some returns can be obtained sooner, through thinning or an "allowable cut effect." Risk of fertilization investment loss (due to fire, insects, disease, windthrow, etc.) increases with time from fertilization to harvest, favouring fertilization of stands near rotation age.

In some localities fertilization may help to accelerate merchantability and increase wood volume in certain stand age classes, minimizing future uneven flow of timber to mills. In this case, fertilizing relatively young stands may be advantageous.

1.4 Tree Size and Stocking

Unspaced stands may be considered suboptimal for economic fertilization, first, because much of the growth response from fertilizer may be lost to mortality, rather than contributing to merchantable volume; and second, because competition for requirements other than the fertilizer nutrient(s) may limit the magnitude of the response.

When tree size is an important factor in utilization and log value, fertilization may yield benefits by accelerating diameter growth. Combined thinning and fertilization results in concentration of growth response on relatively few stems, accelerating the onset of merchantability, enhancing value per unit wood volume (e.g., in the case of sawlogs), and also reducing harvesting costs per unit wood volume. These effects may be particularly important in areas where mature tree sizes tend to be small or where thinning is feasible.

1.5 Regional Climate

In a preliminary assessment, stands in less humid areas at relatively low elevations in the south coastal region of British Columbia should not be disqualified on the basis of climate. Although water stress may limit growth response to fertilizer on some sites on eastern Vancouver Island and similar "rain shadow" areas, positive results of fertilizer trials have been obtained on some sites of such areas.

Little forest fertilization has been conducted in subalpine forests. The same can be said of boreal and sub-boreal forests in the interior of British Columbia. A short growing season in these forests may limit growth responses sufficiently to make fertilization uneconomic. Whether, or under what conditions, growth responses are limited cannot yet be inferred from available data with sufficient confidence for decision-making. Fertilizer studies in interior Alaska and Scandinavia indicate that significant growth responses can occur in boreal forests. Clear indications of volume growth responses and an associated economic analysis would be useful to assess feasibility in British Columbia; but without such information, the uncertainties may discourage fertilization investments. This is particularly the case if the investor has attractive fertilization opportunities elsewhere.

Where total annual precipitation is less than about 50 cm, growth limitations associated with water stress will likely result in uneconomic fertilizer responses. Exceptions to this might exist on sites where available water storage capacity, downslope seepage, or limited drainage in depressional areas reduces the severity and duration of water stress. However, such exceptional sites are likely to be too small for cost-effective fertilization.

1.6 Soil Characteristics and Properties

Certain parent materials or parent material-drainage combinations may preclude straightforward fertilizer prescriptions even if nutritional problems exist. In some situations soil depth, texture, organic matter content, drainage, and moisture content may limit potential fertilizer response. Field examination of such factors can aid a manager in deciding whether to invest in foliar and/or soil sampling for diagnosis of nutrient deficiencies, and may contribute to diagnostic interpretations. The report "Site Diagnosis, Tree Species Selection and Slashburning Guidelines for the Vancouver Forest Region" (Klinka et al. 1984), or other relevant ecosystem guides, may be useful for evaluating these factors.

1.61 Parent Materials

1.6.1.1 Ultramafic materials

Growth of trees and other plants on soils derived from ultramafic materials may be limited by low Ca or low Ca/Mg ratios, possible nickel and/or chromium toxicity, and in some areas, molybdenum deficiency. It is therefore useful for the manager to consult a bedrock geology map of the area to determine whether ultramafic (ultrabasic) rocks (e.g., dunite) or magnesium-rich minerals (e.g., certain pyroxenes, olivine, serpentine, talc) are dominant or prominent in the area. If so, surficial deposits may reflect such materials. Inspection of minerals on freshly-chipped facets of gravel or cobbles from a soil pit at the candidate site may be useful in helping the manager infer whether this factor must be taken into account. In general, ultramafic rocks (like several others) are often dark greenish to black in colour and are relatively coarse-grained. The text by Deer et al. (1966) may be useful for field or laboratory mineral identification. If any evidence suggests that ultramafic materials might be dominant, this information should accompany samples collected on the site for nutrient deficiency diagnosis, so that the samples will be analyzed for Ca and Mg (and perhaps for Ni, Cr, and Mo).

1.6.1.2 Limestone and other calcareous materials

Under good drainage conditions, because of their high pH, calcareous materials may be associated with inadequate availability of iron and (perhaps) manganese. Copper and zinc availability also tends to be lower at higher pH levels. Near-surface calcareous materials can preclude normal applications of urea or ammonium fertilizers, because their high pH would tend to cause volatilization losses and temporary toxicity due to production of ammonia and (in some soils) nitrite.

The forest manager should consult a geologic map to determine whether calcareous materials such as limestone are prominent in the area. If soil survey reports or soil profile descriptions are available for the area, they can be examined to determine whether Ck horizons (calcareous parent materials) are present, and whether horizons with a "k" symbol occur near the surface. Freshly chipped facets of gravel fragments from the soil pit may be tested with dilute (10%, in water) hydrochloric acid. Evolution of bubbles indicates calcareous material. If calcareous material is present, the uppermost depth at which it can be found in the profile should be noted and the soil drainage class assessed (Dumanski 1978). This information can aid interpretation of K, Ca, and various micronutrient analyses of foliage samples, as well as prescription of ameliorative site or stand treatments.

1.6.1.3 Igneous parent materials

Research currently in progress (Klinka and Carter 1983; Carter et al. 1984) suggests that a number of possible micronutrient deficiencies (e.g., zinc, and boron) may be more common in soils whose parent material mineralogy is primarily igneous in origin (e.g., quartz and granodiorites, andesites, basalts, etc.). Low concentrations of these micronutrients appear to be most common in areas of high rainfall with gravelly, coarse-textured soils low in soil organic matter and often having thin forest floors.

1.6.2 Soil depth

The interim recommendation is that the depth of the root zone should not be limited by bedrock or compacted till, or a permanent water table within 50 cm of the surface if fertilization is to be justified by volume growth. At present, no minimum depth recommendations are suggested for rehabilitative fertilizer treatments (i.e., treatments that enable attainment of merchantable form or that reduce top damage, etc., in stands displaying growth abnormalities).

1.6.3 Soil texture and organic matter content

As soils become finer in texture and higher in organic matter content, their ability to retain nutrients normally increases because of relationships with cation exchange capacity and immobilization of nutrients in organic forms. Coarse soils low in organic matter may have an insufficient nutrient retention capacity to prevent large leaching losses after conventional application of macronutrient fertilizers. These soils may also lack sufficient urease activity to allow normal hydrolysis of urea fertilizer. Where normal ureolysis occurs, their low buffering capacity may result in large volatilization losses where urea is applied. Such extreme conditions are seldom encountered in ordinary forest soils, but can sometimes be found where fertilizer use is contemplated for very young plantations on severely disturbed forest soils, for example, where surface horizons have been removed during mechanical site preparation or broadcast burning.

1.6.4 Drainage and soil moisture regime

Douglas-fir growth tends to be best under imperfectly to moderately well-drained soil conditions, i.e. where soil moisture is characterized as fresh to moist (Klinka et al. 1984). Growth response to fertilizer is likely to be greatly reduced by extreme deviations from this optimum range. Soil drainage and moisture conditions affecting fertilizer response of other British Columbia species have not been evaluated here, although some data exist for them in British, Scandinavian, and Central European work.

1.7 Other Limiting Factors: Insects and Disease

Evidence of insect or disease problems that might limit fertilizer response should be sought. Some insect and disease problems are ameliorated by fertilization; others are worsened. For a review of information on this topic, see Foster (1968). In general, fertilizers that promote vigour reduce foliage diseases; however, excesses, deficiencies, and imbalances of nutrients often have the opposite effect. The effects of growth-stimulating fertilizers on various root rots is quite variable: Fomes annosus root rots may be favoured by fertilization while Phellinus and Armillaria vigour may decrease (Foster 1968; Nelson 1970, 1975, 1976).

Control of insects and fungal pests alone will rarely, if ever, justify the costs of fertilizing forests. Where timber growth response from fertilizers justifies the costs, reduction of pest damage might be an extra bonus. In situations where fertilizers are of borderline value in achieving a growth response, the potential to reduce pest damage might theoretically be enough to determine whether or not the candidate stand or site deserves further consideration. In practice, however, the risk of response reduction due to damage, which in extreme cases means losing the whole fertilization investment, suggests that the limited funds available for operational fertilization should be allocated to stands where predicted returns on investment are larger and more certain to be attained.

1.8 Visual Symptoms of Nutrient Deficiencies

Field observations of anatomical and morphological abnormalities may be used as an aid in preliminary assessment of candidate stands. The most common visual symptoms in conifers are discoloration, twisting, fusing, shortening, or premature fall of needles; resin exudation; and twisting, crooking, or dieback of young shoots (Morrison 1974). Table 1 summarizes common symptoms of relatively severe nutrient deficiencies in conifers. Occurrence of such symptoms can help identify stands likely to give good growth and form response to fertilizers (although some response-limiting factors may not be evident). Absence of all such symptoms does not preclude response altogether, but may suggest that deficiencies are insufficient for fertilization to yield the large responses needed to attain good returns on investment.

The appeal of identifying nutrient deficiencies from visual symptoms resides in the method's potential simplicity and the fact that laboratory facilities are not required. However, although needles appear to be particularly sensitive indicators of deficiency, not all deficiencies exhibit distinctive symptoms. For example, general chlorosis (yellowing) can be caused by a wide variety of deficiencies that interfere with chlorophyll

TABLE 1. Visual symptoms of nutrient deficiencies in conifers (condensed mainly from literature reviews of Morrison 1974; Kolari 1979; and Mengel and Kirby 1982)

Deficient element	Visual symptoms
N	Poor growth rate, often with shortened vegetative growth stage. Needles are often stunted with evenly distributed chlorosis generally occurring first in the older needles. Purple tipping and necrosis occur only at a rather late and severe stage of deficiency.
P	Symptoms are primarily in the older needles. Youngest needles green or yellow-green; older needles distinctly purple-tinged; purple deepens with severity of deficiency; in very severe cases in seedlings, all needles may be purple.
K	Variable symptoms. Often no immediate visible symptoms. Needles usually short, chlorotic, with some green near base and, in some severe cases, purpling and necrosis with top dieback; or purpling or browning or necrosis, sometimes with oldest needles most affected.
Ca	Symptoms first observed in the growing tips and youngest needles. General chlorosis followed by necrosis of needles, especially at branch tips; in severe cases deficiency may result in death of the terminal bud and top dieback; resin exudation may also occur.
Mg	Deficiencies begin in older and move to younger needles. Yellow tipping, bronzing and/or banding of needles, needle tip necrosis in severe cases.
S	General chlorosis of foliage.
Fe	Diffuse chlorosis (in mild cases, more evident in young foliage) with bright yellow discoloration in more severe cases. Retarded leader growth, shoot dieback, and bud disorders. Young needles are often short, twisted, and necrotic. Roots are often sparse and reddish brown in colour.
Mn	Variable symptoms: needles may be slightly chlorotic; in severe cases some necrosis of needles may be evident.

(cont'd)

TABLE 1. cont'd...

Deficient element	Visual symptoms
B	Shoot, tip, and/or bud dieback generally occur late in growing season resulting in a proliferation of secondary leading shoots, retarded height growth, and bushiness. Leader often turns reddish brown prior to dieback. Crooked, bent, distorted leaders, often enlarged, brown or necrotic pith. Variable foliar symptoms, if evident generally occur as chlorosis, necrosis, or bronzing at needle tips.
Zn	Extreme stunting of trees with shortening of often erect and thin branches. Chlorosis (sometimes with bronzed needle tips), premature needle fall with resultant tufting of current needles; in severe cases top-dieback and rosetting.
Cu	Crooked, distorted, downward bent, pendulous leaders. Needles twisted spirally, yellowed or bronzed; tipburn or necrosis of needle tips evident; in severe cases young shoots twisted or bent.
Mo	Needles occasionally long and blue-green in colour, more often chlorotic followed by necrosis of tissue, beginning at needle tip and eventually covering whole needle.

synthesis. Chlorosis varies in pattern (the extent to which young and old tissues are involved) and severity (according to the species, the element, and the degree of deficiency). In British Columbia, chlorosis most often seems to be associated with a lack of nitrogen, but it can also be caused by deficiencies of sulphur, calcium, magnesium, potassium, iron, manganese and other elements as well as by numerous unfavourable environmental factors such as moisture deficiencies, unfavourable temperatures, insects, disease and an excess of some micronutrients. However, the yellow tipping caused by magnesium deficiency, the leader dieback indicative of a boron deficiency, the rosetting resulting from low zinc, or the spiralling, tip-burn and pendula symptoms of copper deficiency could, if the deficiency were severe, be distinctive enough to be useful (Morrison 1974).

The absence of observable deficiency symptoms does not preclude the existence of nutrient deficiencies - nutrient deficiencies severe enough to

impair growth are not always severe enough to cause visible symptoms. Moreover, symptoms of multiple nutritional problems are difficult to interpret. After alternative causes of visual symptoms have been considered, more definitive diagnosis by means of foliar analysis may be undertaken for candidate sites that merit further consideration.

1.9 Prospects of an Economic Growth Response

Prospects of a suitable economic return on the fertilization investment depend not only on the magnitude of growth response but also on the applicable economic model (sensitive to such factors as fertilization timing relative to harvest). A mathematical model for predicting Douglas-fir volume growth response to nitrogen fertilizer has recently been developed and calibrated with data from Washington and Oregon (Ballard 1983[1]) and a revised version of the model is currently being examined (Ballard 1984). A computer program for simple economic analysis and another for priority ranking of candidate stands have also been developed (Ballard 1983[1]).

For species and sites where such alternatives are not applicable, the following rationale may be useful. If volume increment in an unfertilized stand is substantially less than that found in stands of similar age and stocking (expressed as a percent of normal stocking) on the best sites of similar soil moisture regime, and in the same climatic region (biogeoclimatic unit), the difference in increment presumably reflects a serious nutrient limitation. In this case fertilization might be profitable, and this could possibly justify more precise evaluation of stand nutrient status, such as with foliar analysis.

[1] Ballard, T.M. 1983. Douglas-fir fertilizer prescriptions. Fac. Forestry, Univ. of B.C., Vancouver, B.C.

2 SAMPLING AND ANALYSIS OF SOIL AND FOLIAGE FOR NUTRIENT STATUS EVALUATION IN CONIFEROUS STANDS OF BRITISH COLUMBIA

2.1 Comparative Roles of Foliar Analysis and Soil Analysis

Scientifically rigorous proof of nutrient deficiencies is too time-consuming and expensive for routine diagnostic use. The two tools most commonly used for nutrient deficiency diagnosis are soil analysis and foliar analysis. Both methods are subject to some interpretive imprecision but each allows certain useful kinds of inferences. The advantages and limitations of each of these methods must be recognized before a decision to use one or the other can be made.

Soil sampling and analysis are both time- and cost-intensive. Sampling (either by horizon or depth) normally needs considerable replication to provide a reasonable standard of precision and confidence. For relatively complex nutritional evaluations, soil analysis may involve determination of such properties as pH, cation exchange capacity, and concentration of exchangeable cations, total nitrogen, organic carbon, "available" phosphorus, extractable sulphate, mineralizable nitrogen, and "available" iron, aluminum, copper, zinc, manganese, boron, and molybdenum. There are a number of significant limitations and disadvantages in the application of this method. First, costs of sampling and analysis can be prohibitive. Second, the often extreme variability of forest soils may require that an excessive number of samples be taken in order to provide a representative sample. There are also difficulties with the selection of what part of the soil to sample. Sampling by horizons can be difficult if they are discontinuous or of variable thickness, thus complicating sample replication; sampling at pre-defined depths may result in very different samples between locations.

Correlations between soil characteristics and tree nutrition and growth, necessary to the development of diagnostic tests, are often very species- and site-specific. Their development has often been slowed by the sheer volume of effort required to evaluate various methods of determining extractable, exchangeable, or available forms of a wide range of soil characteristics in each of several depths or horizons. The statistical significance associated with such correlations is sometimes too low to be of great diagnostic value. However, soil sampling and analysis can sometimes be very useful for estimating the supply, form, and availability of certain nutrients. Soil sampling can also help the manager infer possible reasons for nutrient deficiencies, such as immobilization of nitrogen due to a wide C:N ratio; poor nutrient uptake due to impaired root development, possibly as a result of poor aeration or compaction; or pH-related availability problems. Such inferences can be useful in the identification of management practices likely to enhance nutrient availability.

While soil analysis tries to measure the supply of elements presumably available in soil, foliar analysis provides an index of the amount actually taken up by the stand. Sampling, analysis, and data interpretation tend to be less complex and time consuming for foliage than for soil; consequently, use of foliage tends to be less expensive. Soil analysis, with its different horizons, depths, humus forms, textures, coarse fragment contents, and root distributions, and the problems associated with compositing samples and interpreting data, is often very complex.

For the purpose of operational forest stand nutrient status evaluation, foliar analysis is recommended as the most suitable preliminary diagnostic technique. At present, foliar analysis is most useful for the identification of severely deficient nutrients, though it can also identify certain incipient deficiencies. As better methods of data expression are developed and further work on optimum and critical nutrient levels and ratios is carried out, it will likely become more useful in identifying these more subtle deficiencies.

Sampling and analysis of the mineral soil and/or forest floor are suggested as an aid to identifying the possible causes of, and remedies for, the nutrient deficiencies identified through foliar analysis. The actual soil analysis recommended will depend on the deficiencies being examined.

2.2 Sampling Guidelines

The guidelines given in this section are intended to supply useful and cost-effective information for silvicultural evaluation of forest stand nutrient status. They are not necessarily adequate for research purposes. Sampling for routine diagnosis must closely conform to the sampling criteria that were used for collecting the research data on which interpretations are to be based. Therefore, modification of routine sampling guidelines should only be undertaken when appropriate interpretive data are available.

Interpretations of soil analytical data are dependent on the assumption that the data are representative of the site. Soil nutrient content can differ markedly both within and between profiles, horizons, and depths. Interpretations of foliar data, although applicable to the whole stand, are normally based on data from samples of a particular stratum defined in terms of crown class, crown position, foliage age, season, etc. Even with such stratified sampling, variation remains. Therefore, sufficient samples must be collected to ensure an appropriate level of statistical precision and confidence. The appropriate level depends on the precision with which interpretations can be made and on the frequency and gravity of the

particular nutritional problem being examined. (For example, infrequent, minor problems, and low interpretive precision do not justify highly precise estimates of population mean data.)

A number of studies have been carried out to determine the number of samples necessary to provide particular levels of precision and confidence for various analyses of mineral soil (Lewis 1976; Slavinsky 1977); forest floor (Grier and McColl 1971; Quesnel 1980; Carter 1983); and foliage (van den Driessche 1974; Ballard 1981[1], 1982[2]; Richter 1983). Furthermore, Ballard (1981[1], 1982[2], 1983[3], 1985) has attempted to estimate appropriate levels of precision and confidence for various foliar nutrients in some British Columbia conifers.

For the purpose of routine forest stand nutrient status evaluation, foliage sampling of 15 trees (coastal Douglas-fir) or 20 trees (other species) per stand seems to be adequate in nearly all cases. The sampling intensity suggested will normally be sufficient to provide adequate levels of precision and confidence for most macro- and micronutrients (N, P, K, Mg, S, Cu, Zn, and B). Due to the often greater variability of Ca, Fe, and Mn, a larger number of samples (30-100^{+} per stand or site) would be required to provide a similar level of analytical precision. However, because deficiencies of these nutrients are infrequent and interpretive precision is relatively low, this intensity can rarely be justified. Similarly, 15 forest floor samples is normally enough to represent a stand, and 15 mineral soil samples taken from within 30 cm of the surface will also be adequate in many situations where soils are fairly homogeneous. Fewer samples may be required at greater depth. In heterogeneous stands possessing a mosaic of site conditions (such as multiple soil subgroups, variable soil moisture regimes, or heterogeneous surface soil conditions due to management disturbance), stratified sampling is appropriate, with a minimum of 10 samples of foliage (or forest floor or mineral soil) taken in each stratum of significant extent.

When sampling foliage, mineral soil, or forest floors, the forest manager should make notes describing the area and the ecosystems included (i.e., the stands and sites) and for each sampling stratum, record location, slope, aspect, elevation, biogeoclimatic subzone or variant, soil

[1] Ballard, T.M. 1981. Foliar analysis research. Fac. Forestry, Univ. of B.C., Vancouver, B.C. 132p.

[2] Ballard, T.M. 1982. Foliar analysis research. Fac. Forestry, Univ. of B.C., Vancouver, B.C. 19 p., 13 appendices.

[3] Ballard, T.M. 1983. Douglas-fir fertilizer prescriptions. Fac. Forestry, Univ. of B.C., Vancouver, B.C. 17p., 7 appendices.

moisture and nutrient regimes, ecosystem or site unit, soil drainage class, and soil parent material (particularly if it is calcareous or mineralogically unusual). If extrapolation of data to or from other sites is anticipated, a soil description (suitable for identification of the soil family or, where possible, the soil series) will be needed. Stand information should include the tree species of each sample and significant characteristics (e.g., cones, foliar or growth abnormalities, or other evidence of stress). Any deviations from recommended sampling guidelines should be noted, along with the sample identifying numbers. Record should also be made of stand age, stocking, and composition, as these data facilitate prediction of response to nitrogen fertilizer, and will also be needed if extrapolation of data to or from other stands is anticipated. For further information on measurement of the above parameters see Walmsley et al. (1980).

2.2.1 Foliar sampling guidelines

Unbiased sampling that fairly represents the whole stand is desirable, but the method of approximating such sampling must be reasonably simple and efficient for routine operational use. The following procedure is suggested.

For a stand where stratified sampling is unnecessary, set up two or more well separated transect lines that cross the stand and also cross any major topographic features. After excluding portions of the lines, by using Guideline 4 (below), establish equally spaced reference points on these lines, corresponding to the number of trees to be sampled. From each reference point, select the nearest tree that meets guidelines 2 and 3 (below).

For stratified sampling, where a stratum occurs as numerous small "islands" within the stand, use the same transect method to identify islands and trees to be sampled. If a stratum occurs as one large island, use the above transect appproach within the island, to identify individual trees for sampling. (This amounts to sampling each stratum as if it were an individual stand.) If a stratum occurs as two or more large islands, it is appropriate to use one transect line in each of two (or more) of the largest islands.

The guidelines are as follows:

1. Sample conifer foliage during the dormant season, preferably between September 15 and December 15. (Larch should be sampled before foliage colour change. However, interpretive criteria for western larch data have not been found).

2. Confine sampling to dominant and codominant trees.

3. Avoid trees likely to yield poor samples because of heavy cone production, insect, or disease damage, etc. If such avoidance is impractical, these factors should be taken into account in laboratory analysis and data interpretation. Analysis of individual (rather than composite) samples is recommended if sample trees vary with regard to these factors.

4. Avoid sampling foliage near unpaved roads or in other situations that may lead to foliage contamination from dust. This is particularly important on well-drained calcareous soils, where iron deficiency diagnosis is needed.

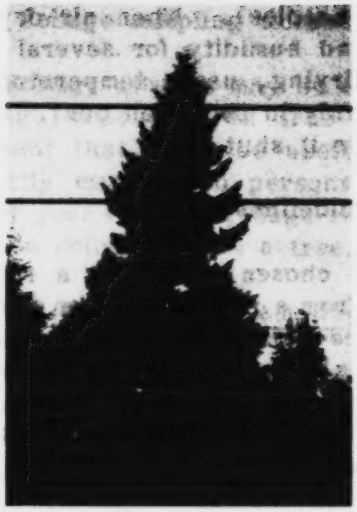
5. Estimate the distance from top to bottom of the live crown. Collect samples at about 1/4 to 1/2 of that distance from the top. If composite samples are to be prepared, sample two branch-ends per tree and collect a 2 g (fresh mass) subsample of the current year's foliage (terminals and/or laterals) from each branch (Figure 1). This gives 4 g per tree and, if 15 trees are sampled, 60 g per stand. If individual trees are to be analyzed, a minimum of 25 g (fresh mass) should be collected for each tree.

Colour and size criteria are likely the easiest to apply when current and previous year's foliage are being separated. The colour of foliage is often different for different foliage ages, and can vary from stand to stand. Current year's foliage is often a somewhat paler or yellower green. Twigs are invariably darker on previous year's than current year's shoots, as are fascicle sheaths in pines. Twig diameter is usually larger in terminal shoots that developed during the previous year; and the terminal buds of such shoots, if they have failed to flush, are often larger in diameter and somewhat longer than current-year buds. Care should also be taken to avoid sampling lammas and/or proleptic growth.

6. Usually it is best to put samples into labelled plastic bags, although samples collected under dry conditions can be put into labelled paper bags. Dirty samples should be discarded and replaced.

7. Drying of samples should begin as soon as possible, preferably on the day of sampling. However if samples are kept cool (1-5°C), drying may be deferred as much as a week and perhaps longer. It may be easiest to ship samples directly to the analytical laboratory if prompt transport and handling can be arranged. If samples must be dried before shipment, oven-drying is best. If no oven-drying facilities are available, thorough air-drying should be done.

For drying it is most convenient to transfer samples to short, fully-opened paper bags (e.g., lunch bags, with the top half rolled down or cut



1. Sample from uppermost 1/2-1/4 of the live crown, excluding top 3 branch whorls.

2. Collect a minimum of 2 branches per tree.

3. Collect sample of current years foliage only.

4. Collect a minimum of 2.0 g of needles (fresh mass) from at least 3 branchlets per branch.

FIGURE 1. Field sampling methods - foliage collection.

off) on which the sample number has been written. Before drying, remove and discard twigs, bud scales, and other non-foliage material (fascicle sheaths are not normally removed from pine needles). When air-drying, leave the bags at ordinary room temperature and humidity for several days preferably with forced-draught. When oven-drying, use a temperature of 70°C for 8-12 hours, or until needles snap cleanly in two when bent. After drying, fold the top of the bag over and staple it shut.

2.2.2 Mineral soil and forest floor sampling guidelines

1. Fifteen subsampling locations should be chosen by either a random procedure (i.e. taking pairs of numbers from a random number table -- the first number representing a distance along the Y-axis and the second number a distance along the X-axis); or a systematic procedure (i.e., taking samples at pre-defined intervals along one or more transects depending on the shape of the stand). If sampling is to be stratified, a systematic sampling procedure is likely the easiest.

2. Avoid subsampling locations in, or under the influence of, standing water, decaying wood, stumps, and exposed rock. However, in some soils, decaying wood may represent a considerable component of the rooting medium. In situations where decaying wood is well-decomposed and/or has a considerable component of fine roots, it can be sampled either separately or as a part of the forest floor.

3. At each subsampling location a 25 x 25 cm sample of the forest floor should be excavated down to the mineral soil, and the thickness of each subsample recorded. Mineral soil subsamples of approximately 500 g each should be taken at 30-cm intervals to the bottom of the rooting zone. Coarse fragment content should also be estimated for each 30-cm depth (coarse fragment content = percent of soil solids made up of rock fragments greater than 2 mm in diameter estimated on a volume basis). All samples should be placed in labelled plastic bags.

4. Mineral soil subsamples can be composited in the field or laboratory by samples of equal volume being combined in a large basin or pail and the contents being thoroughly mixed. A composite sample of approximately 500 g can then be taken and prepared for laboratory analysis. Forest floor samples should be dried before compositing in the laboratory. Both mineral soil and forest floor samples should be air-dried at room temperature (25°C) until the samples reach a constant weight ($\pm$ 2%) as soon as possible following collection.

2.3 Sampling Methods

2.3.1 Foliage sampling methods

Foliage samples may be collected from the ground, by climbing or by shooting, depending on tree height and form. A checklist of sampling equipment that might be useful is given in Table 2. Foliar sampling can efficiently employ two persons: one collecting while the other separates current year's growth, bags the samples, indicates when a sufficient sample has been collected from a tree, labels bags, and records field notes.

2.3.1.1 Ground sampling

If trees are less than approximately 10 m tall, samples may be collected with a hand pruner, long-handled orchard pruner, or telescopic pruning pole. However, most forest stands must be sampled by climbing or shooting methods, as they are too tall for ground sampling.

2.3.1.2 Climbing

Climbing for samples is most feasible in stands less than 30 m in height. Groups of three to five trees can be sampled throughout the stand by the researcher climbing and sampling a dominant tree in the middle of each group and sampling adjacent trees by reaching horizontally with a telescopic pruning pole. This minimizes climbing time as well as the risks associated with climbing.

Climbing involves considerable risks and should only be undertaken by experienced personnel in the presence of other workers. Choosing equipment involves some personal preference and might include spurs, belt, sit-harness, slings, and a rapelling rope, as well as a lightweight telescopic pruning pole. Coveralls are needed to protect clothing from resin, dirt, and abrasion. To be left free to climb, the climber normally carries the pruning pole up on a light rope. When at a satisfactory height it is best to clip the sit-harness into at least two slings around the main stem. A sit-harness (Troll or Whillans-type) provides more comfort, safety, and mobility than a belt. After sampling, the researcher can quickly descend the tree by rapelling, if there are few branches, or climbing down.

2.3.1.3 Shooting

Shooting down samples is the only practical alternative in forest stands greater than 30 m in height, though it can also be a relatively easy and efficient sampling method in shorter stands. If properly conducted it can be less hazardous than climbing for samples.

TABLE 2. Equipment checklist: conifer foliage sampling for nutrient deficiency diagnosis

Field notebook and pencil		
Ruler or tape measure		
NTS 1:50 000 and 1:250 000 maps or forest cover maps		
Air photos (with Mylar overlays, waterproof case)		
Plastic sample bags with closures and labels		
Paper bags, stapler, staples		
Boxes for transporting samples		
Backpack, first-aid kit		
Lightweight, portable field scale		
Hand pruning shears		
Telescopic pruning-pole(s)	lightweight (Fiberglass)	4 m
	Multi-section (Dural)	8 m
Coveralls, climbing spurs, sit-harness, belt, slings, and rapelling rope (50 m). Clothing to provide recoil padding, for shotgun use.		
Hearing protection, shooting glasses		
Targets for checking and adjusting rifle sights		
Shotgun/rifle, Savage Model 24C or equivalent, 20-gauge full-choke, .22 rimfire for short, long, and long rifle, with iron sights, 2x telescopic sight and recoil pad[a]		
Shotgun, 12-gauge full choke, with iron sights and recoil pad[a]		
Rifle, .22 rimfire, suitable for short and long rifle, with 4x (or 2x) telescopic sight[a]		
Suitable ammunition[a]		
Firearms Acquisition Certificate (if firearm must be purchased or borrowed)		
Provincial firearms permit or hunting licence		
Firearms cleaning kit		

[a] See Table 3 for selection of firearms and ammunition.

To acquire a firearm, one must obtain a Firearms Acquisition Certificate from the police or RCMP office responsible for the town or municipality of one's principal residence. The cost is $10.00. To carry a firearm, one must obtain a provincial firearms permit or hunting licence from a hunting or sporting goods shop. The cost is $2.00. Several restrictions pertaining to firearms exist, among them: it is illegal, as well as unsafe, to have a loaded firearm in or on a vehicle.

Technique is involved in shooting, as a falling twig may be caught by branches in mid-crown and require additional shots. It has been suggested that selection of an appropriate firing angle can exploit the bullet impact to push samples slightly toward holes in the canopy.

Shooting, because of its hazards, cannot be unconditionally recommended and should only be assigned to responsible, safety-conscious personnel. The major safety concerns are the possibility of injury to the sampler from failure to observe ordinary firearms safety precautions, and the possibility of injury to someone who, unknown to the sampler, is within range. Because the latter problem is enhanced by firing upward into the tree crown, rather than against a safe, visible backstop, the firearms, ammunition, firing directions, and vertical angles of fire should be selected to minimize bullet range and maximize shooting accuracy.

It is safest not to load until at the location from which one intends to fire. Care should be taken to avoid obstructing the firearm barrel with, for example, dirt or snow. Shooting glasses should be worn when firing.

It is appropriate to set up warning signs at points corresponding to maximum range and along nearby roads, and to check for parked vehicles in the area before the start of sampling.

Shotguns: Shotguns are very useful for sampling and their limited range makes them attractive from the safety standpoint. Also, their shot pattern makes them effective for sampling under windy conditions, when branches are swaying. For most stands, a full-choke 20-gauge, firing 2-3/4 inch shells with 1 oz. of No. 2 shot is very effective. The low recoil of the 20-gauge makes it desirable for routine use. For taller stands, a full-choke 12-gauge, firing 3-inch shells with 1-5/8 oz. of No. 2 shot is slightly superior, because of the greater pattern density at longer range. No. 2 shot is suitable for most species, because it is small enough to provide good pattern density and large enough to give a high probability of severing a hit twig. No. 4 shot is usually adequate for most interior conifers. The shotgun should be equipped with iron sights. Hearing protection and ample recoil padding are mandatory when a shotgun is used for foliage sampling. A disadvantage of the shotgun is the high cost of ammunition.

Rifles: Rifles permit greater range, but consequently can involve greater hazard to persons downrange. To limit the hazard, it is desirable to use the minimum cartridge load necessary and to aim at a very steep angle. Accurate shooting reduces the number of shots and the range of the bullet, improving safety. The most versatile rifle calibre for the purpose is the .22 rimfire. The rifle should accommodate a variety of ammunition, from low velocity .22 short ("CB") to high velocity .22 long rifle. An autoloading rifle is inappropriate, because it is not suited to low velocity ammunition. Any .22 rifle that takes .22 shorts will take the CB cartridges. Several current CB cartridges (e.g., those manufactured by Winchester-Western and CCI) have the same dimensions as the .22 short. The .22 long has only slightly greater range and velocity than the .22 short, but is slightly less accurate than either the .22 short or the .22 long rifle (Barnes 1965), and therefore offers no advantage for foliage sampling. Hollow-point bullets may be useful for sampling species with thick or tough twigs such as Douglas-fir or Sitka spruce. According to Barnes (1965), the .22 short and long rifle both have a maximum range of nearly 1 mile (1.6 km) and maximum range is attained at a rather low firing angle: about 25° to 30°. The .22 rimfire requires no recoil protection. Hearing protection is generally recommended, although it may be unnecessary for the low velocity cartridges.

Except for sampling at relatively low heights, a telescopic sight should be used on the rifle. A 2x scope may be adequate, but 4x is desirable for taller trees. After some experience with each type of cartridge, one should note the difference in scope setting between that needed for accurate nearly vertical shooting and that needed for accurate nearly horizontal shooting at the same distance. Once a table of such differences has been prepared, sights can be readily adjusted by the appropriate difference after conventional "sighting in" by horizontal firing at a safe target has been done. This procedure will contribute to safety as well as to sampling efficiency.

Selection of Firearms and Ammunition: Accuracy, efficiency and safety are major considerations in firearm selection. Ease of disassembly and cleaning is also important if much sampling must be done. If a single firearm must be selected for foliage sampling, versatility is important. The best of these is the Savage Model 24C, which has an over-and-under .22 short, long, long-rifle barrel over a full-choke 20-gauge shotgun barrel (which takes 2-3/4 inch, and in some versions 3-inch shells). This is a single-shot firearm with iron sights and grooved receiver for scope mounting. (A telescopic sight on this firearm should be removed before the shotgun is used to avoid face injury from the short eye-relief scope). The firearm quickly breaks down into two 50-cm sections for easy carrying or storage. Approximate cost of this rifle/shotgun with 2x scope, case, and cleaning kit is $400.00.

Sampling efficiency for a range of tree heights may be improved if as many as three firearms are available:

1. A full-choke 12-gauge shotgun with iron sights.

2. The Savage 24 or 24C with iron sights, for 20-gauge shells and .22 cartridges.

3. An accurate, scoped .22 rifle, suitable for short, long, and long-rifle cartridges.

Table 3 can serve as a guide for the selection of adequate, minimum-load ammunition for sampling. The sampling height ranges for various ammunition were estimated on the basis of field experience, and should not be considered highly precise.

Shooting Positions: With shotguns, offhand shooting is adequate. For use of .22 rimfire ammunition at all but the shortest ranges, accurate sight adjustment and a stable shooting rest are important. Prolonged upward shooting from a standing position puts strain on the back and neck muscles, causing discomfort and loss of accuracy. With the low recoil .22, these problems can be avoided if one lies on one's back, bracing the rifle-supporting arm against a knee or tree stem.

2.3.2 Mineral soil and forest floor sampling methods

The equipment used in sampling soils is relatively straightforward. Standard equipment includes shovel, mattock, pruning shears, pruning saw, hand spade, measuring tape, gloves, plastic bags, and labels.

Forest floor samples should be classified and sampled before mineral soil samples. As stated in Section 2.1 of this paper, compositing samples by horizons can be extremely complex; therefore, it is suggested that the forest floor L, F, and H horizons be combined to form a separate sample at each subsampling location, and mineral soil samples be collected at 30-cm depth intervals to the bottom of the rooting zone. Assistance in describing, classifying, and sampling forest floors and mineral soils may be found in Canadian Soil Survey Committee (1978), Dumanski (1978), and Klinka et al. (1981).

2.4 Laboratory Selection

At present there are a number of commercial laboratories in the Pacific Northwest capable of analyzing foliage, forest floor, and mineral soil materials. If the analysis is part of a government partial reimburse-

TABLE 3. Ammunition selection for foliage sampling by shooting

Height of sampling (m)	Conditions (windless unless otherwise noted)	Recommended ammunition[a]
below 20	windy	20 ga. 2-3/4 in. No. 2 or 4 shot[b]
above 20	windy	20 ga. 2-3/4 in., or 12 ga. 3 in., No. 2 shot[b]
below 25		.22 low velocity short (CB) or 20 ga 2-3/4 in. No.2 shot[c]
25-35		.22 high velocity short or 20 ga. 2-3/4 in. No.2 shot
35-45		.22 long rifle or 20 ga. 2-3/4 in., or 12 ga. 3 in. No.2 shot
above 45		.22 high velocity long rifle or 12 ga. 3 in. No.2 shot
below 40	thick or tough twigs Fd, Ss, Hw, Ba	.22 high velocity short, hollow point.
above 40	thick or tough twigs	.22 high velocity long rifle, hollow point.

[a] These recommendations are tentative, pending completion of tests. However, experience suggests they will be adequate. The minimum effective cartridge load is recommended for safety reasons.

[b] The shotgun may also be used under windless conditions, but its ammunition is more expensive and it requires more hearing and recoil protection.

[c] A telescopic sight is not recommended for sampling at less than about 10 or 15 m because of the sighting error at uncertain short ranges, which is a consequence of scope height above the bore.

ment program (e.g., Section 88), use of a Canadian lab will likely be required. Before a laboratory is selected to do the analysis, the following factors should be examined:

1. Capability. Can it perform the desired analyses? How quickly can it provide results?

2. Experience. Has it previously carried out the analyses requested?

3. Accuracy. Has it produced consistently accurate results with standard samples? Can it provide comparisons of results obtained by the best available methods with the results obtained by its routine analytical methods? Can it furnish comparison of its analytical results with those from other laboratories analyzing the same reference sample?

4. Costs. Are its sample preparation and analysis costs competitive?

5. Reputation. Is there knowledgeable, independent testimony as to its performance?

2.5 Sample Preparation and Analysis, and Quality Control

The following methods of sample preparation and analyses are suggested as being most useful in operational identification of nutrient deficiencies. This list of analyses is by no means complete and there are often suitable alternative procedures to those described in this section.

Foliage, forest floor, and mineral soil materials can be prepared for laboratory analysis by the sampler; however, because of some minor equipment needs it may be easier to have the sample preparation carried out by the lab. The following analyses and methods of sample preparation are recommended for foliage samples. Because the interpretation of many soil analyses depends on the analytical methods used, soil analysis and its interpretation are discussed together in Section 2.7.

2.51 Foliage sample preparation and analysis

Before samples are ground and analyzed, it may or may not be desirable to rinse them in detergent solution, wipe them, and rinse them in distilled water, in order to remove contamination by road dust: some mobile elements might be leached from foliage by rinsing, detergent might contribute to contamination, and this procedure adds to foliar analysis costs. For stands suspected of having Fe deficiency problems, washing and rinsing are essential where contamination from dust has occurred. Therefore, if foliage samples are from stands where Fe deficiency seems likely (as on

well-drained calcareous soils) the samples should be divided into halves: one that is dried and ground, without previous washing, for routine analysis of macronutrient elements; and the other that is rinsed in detergent solution (Liqui-Nox detergent), wiped to remove surface contamination, rinsed quickly several times in distilled water, dried, and ground for analysis of macro- and micronutrients and Al.

If the analytical data are to be used for comparing foliar nutrient status between stands, fertilizer, or other silvicultural treatments, or if the foliage appears stunted, the mass of 100 needles (or needle bundles, in the case of pines) or the mass of needles per shoot should be determined for samples oven-dried at 70°C. If foliar data are not to be used for the above purposes or the foliage does not appear stunted, the cost of this determination may exceed the value of the information.

Dry foliage should be ground for chemical analysis. If a needle snaps cleanly in two when bent, it is dry enough for efficient grinding. Samples are most conveniently ground in a Waring blender stainless steel cup or a Braun type KSM-2 coffee grinder. The largest particle dimension should be no more than about 1 mm after grinding, and there should be no obvious separation of tissues. If the tissues do separate into fibrous and powdery fractions, chopping rather than grinding of foliage should be done. After grinding, samples should be re-dried at 70°C before storage in air-tight, screw-cap plastic bottles. The total oven-drying time for a sample ideally should be no more than about 12 h, but as much as 20 h of oven-drying might not produce any detectable differences in analytical results.

The following analyses are recommended for foliage samples. These will provide most of the data necessary for running the computerized diagnostic program outlined in Chapter 3:

1. Total N, P, K, Ca, Mg, Fe, Mn, Cu, and Zn
2. Total S (Sulphate-S optional)
3. Total B
4. Active Fe (Ballard 1981[1])
5. Total Mo

We have found the following foliar analysis methods satisfactory (Ballard 1985).

1. Digestion by the method of Parkinson and Allen (1975), followed by colorimetric (autoanalyzer) analysis for N (phenol-hypochlorite

[1] Ballard, T.M. 1981. Foliar analysis research. Fac. Forestry, Univ. of B.C., Vancouver, B.C. 132p.

method) and P (unreduced vanadomolybdate complex), and atomic absorption spectrophotometry for K, Ca, Mg, Mn, Zn, and Al.

2. Digestion in nitric acid and hydrogen peroxide, followed by atomic absorption spectrophotometry for Cu.

3. Dry ashing, followed by colorimetric analysis for B, by the azomethine H method of Gaines and Mitchell (1979).

4. Active Fe extraction by the method of Oserkosky (1933), using 1 M HCl, and analysis by atomic absorption (Ballard 1981[1]).

5. S analysis with a Fisher Sulfur Analyzer, as described by Guthrie and Lowe (1984).

Current studies suggest that the nitric acid digestion is also suitable for Mo analysis by atomic absorption, using a graphite furnace. The ICP (inductively coupled plasma spectrograph) may be useful for approximate quantitative characterization of several elements in foliage. However, our experience with the ICP has not yet indicated high levels of accuracy and precision. No inexpensive, routine methods for total Fe analysis are very accurate, judging from our experience and that of Zasoski and Burau (1977). However, active Fe analysis appears to be more useful for diagnostic purposes (Zech 1970).

All data should be reported as percent concentration on an oven-dry mass basis, except that micronutrients (Fe, Mn, Zn, Cu, B, and Mo) may be reported in ppm (i.e., mg/kg).

2.5.2 Mineral soil and forest floor sample preparation

The following methods of sample preparation are suitable for most of the analyses outlined in Section 2.7. Mineral soil samples should be air-dried, crushed with a wooden roller and put through a #10 (2.0 mm) sieve. Forest floor samples should be air-dried, ground in a Waring blender to pass a 20-mesh sieve, and combined to form a composite sample. (A Wiley mill should not be used because of potential damage to blades by mineral particles.) If forest floor thickness is extremely variable (i.e., with deep accumulations in depressions interspersed with shallow forest floors), it may be appropriate to combine samples on an equal weight basis. If differences in thickness are not extreme over short distances it may be preferable to combine samples on a depth-weighted basis to form the composite sample (e.g., a subsample taken where the field depth (thickness) is 2

[1] Ballard, T.M. 1981. Foliar analysis research. Fac. Forestry, Univ. of B.C., Vancouver, B.C. 132p.

cm should contribute twice as much material to the composite sample as a subsample taken where the forest floor is only 1 cm thick). Both mineral soil and forest floor samples should be stored in labelled, relatively air-tight, plastic bags or containers.

2.5.3 Analytical quality control

Quality control checks can be performed with the use of "standard" samples and "reference" samples. Foliage samples for which certified analysis values are provided can be obtained from the U.S. National Bureau of Standards. The certified analysis values are generally dependable because they have been determined by more rigorous and thorough procedures than can be afforded for routine analysis. Occasional checks using such standard samples provide a good indication of analytical accuracy.

Analytical precision is another important consideration. Analysts performing batch analyses often include one reference sample with each batch, to indicate whether results are reproducible. The reference sample is simply a representative subsample from a very large sample. For foliar analysis, a reference sample may consist of a dried, ground, well-mixed sample of all the foliage obtained from a large tree, or of a mixture of old ground foliage samples. For soil analysis, a reference sample may consist of a large container full of air-dried, sieved, well-mixed soil. (An appropriate sieve size, to reduce subsampling difficulty, is the No. 40, which has an opening of about 0.42 mm.) For analyzing the forest floor, a reference sample may consist of dried, ground, well-mixed forest floor material.

Not all laboratories can be counted on to use standard samples or to use their own reference samples with each batch. A laboratory that does should be asked to provide the data it obtained and the certified analysis values for the standard sample. However, the client who expects to send more than one group of samples for analysis will also find it worthwhile to send a subsample of his own reference sample each time, so that the comparability of data obtained over a period of time or from different laboratories can be estimated. Ideally, the reference sample should occasionally be analyzed in the same batch as the standard sample.

When composite samples are analyzed, confidence in the data can be greatly increased if there is some replication of analysis such as analysis of duplicate subsamples, as well as additional subsamples, unless agreement of the duplicate values is adequate. Where several individual samples are examined to characterize a stand (or stratum), replication of analysis is seldom necessary for routine work: variability of results represents combined variability of samples and analytical variability. Unless low analytical precision is indicated by variability of reference sample data,

confidence in the mean obtained from several individual samples will not be much improved by replication of analyses.

2.6 Interpretation of Foliar Analysis Data

2.6.1 Use of critical levels

At present, foliar nutrient status interpretations are based on the findings of research carried out on a number of tree species, often over a wide range of field or greenhouse conditions. Because some nutrient deficiencies have not been examined in British Columbia, interpretations are based on research with British Columbia species in other regions. Fortunately the applicability of foliar analysis interpretations for a species does not seem strongly related to geography. However, other factors (particularly the sampling criteria used) may limit applicability of interpretations developed in some studies.

Most interpretations of foliar analysis data now use the concept of critical levels. The critical level for a particular element is the foliar concentration above which little positive growth response can be obtained when the supply of the element is increased. Beyond the plateau zone of little or no growth response, there is commonly a toxicity zone where increasing nutrient supply results in negative growth reponses. Below the critical level of an element, growth is normally limited by that element (although, in some cases, growth response to additions of the element is limited by other factors).

Inference of precise nutrient status based merely on critical levels would be simplistic. Many biochemical and physiological processes within the tree are optimized not by holding individual nutrient concentrations above some threshold level, but by maintaining certain nutrient element ratios within critical ranges. Also, nutrient concentrations can be reduced when a nutrient element is "diluted" by an increase in the foliar mass. This can occur when growth limitations are relieved by stand or site treatments, such as thinning, irrigation, or fertilization. High concentrations before fertilization may indicate current nutrient sufficiency, which gives way to deficiency when other limiting factors are relieved. Several different methods of examining data that attempt to overcome some of these shortcomings are discussed in Section 2.62.

Most of the currently available interpretations of foliar nutrient data for British Columbia conifers are based on foliage sampled during the dormant season - late September through early December. Those who developed the interpretations chose this season because foliar nutrient concentrations are relatively stable during this time, allowing the same interpretations to be used for samples collected over a period of several

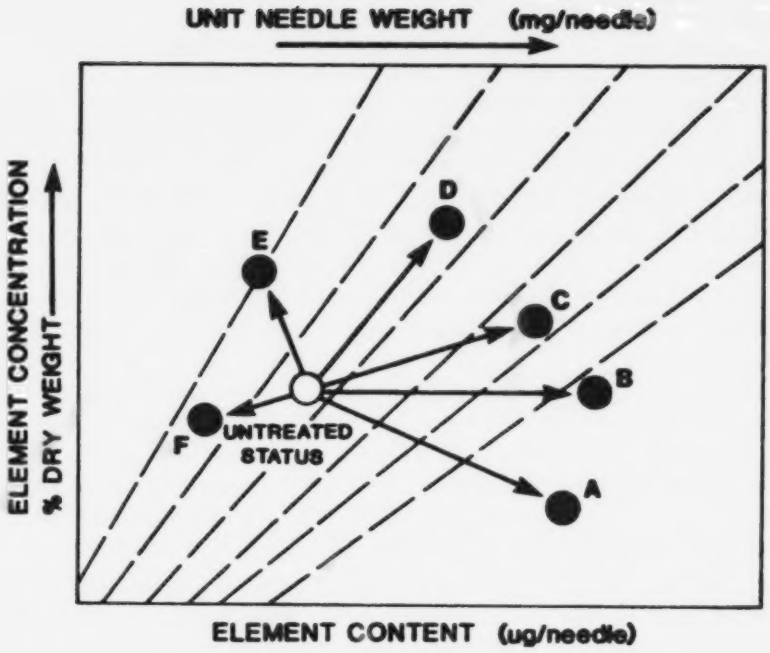
weeks or months. Foliar nutrient levels of dormant season samples sometimes, but not always, reflect nutrient availability during the growing season - the period of greatest need. For mobile nutrients, i.e., those nutrients that can be translocated from older tissues to younger tissues within the tree (e.g., N, P, K, Mg, and S), dormant season foliage samples normally give an adequate representation of the foliar nutrient status during the growing season. During periods of very high demand or interruptions of supply, extreme deficiencies that might damage developing tissues are avoided by internal translocation. However, for the more immobile nutrients (e.g., Ca, Fe, B, Zn, and Mn) dormant season foliage samples may be of limited value in the identification of deficiencies that may have occurred during the growing season. Short interruptions of external supply (as during a severe summer drought) may result in deficiencies of these immobile nutrients, possibly resulting in damage to developing tissues.

2.6.2 Methods of expressing and examining foliar nutrient data

Much research has been directed at developing better methods of evaluating foliar nutrient data. At present the use of foliar nutrient data expressed as percent or ppm concentration on an oven-dry mass basis is the most widely used. Data in this form are then usually compared to critical or deficient levels suggested by hydroponic experiments, pot trials, and experience gained through the use of foliar analysis in the field. Section 2.63 offers a listing of tentative foliar nutrient status interpretations currently applied to conifer species in British Columbia.

Foliar nutrient levels may instead by expressed in terms of content, on a needle number, leaf area, or shoot basis. For example, data may be expressed on a mg/100 needle basis. Foliar concentration data can be put into a mg/100 needle basis by determining the foliage mass/100 needles before needles are ground for analysis, and multiplying by the nutrient concentration, expressed in appropriate units. This is most useful when nutrient trends are compared among stand treatments, as it can help avoid the "dilution" and "concentration" complications mentioned in the previous section. Smith et al. (1981) suggested that this method be improved by having foliar nutrient data placed on a weight per unit leaf area basis, although this requires an estimation of leaf area index and needle surface area measurements, making it more suitable for research purposes rather than for operational foliar nutrient status evaluation. Another alternative, useful for evaluating uptake, is to determine mass of nutrient per shoot.

Heinsdorf (1968) has developed a graphical procedure that uses unit foliar nutrient data expressed both in concentrations and mass of element per 100 needles (mg/100 needles) (Morrow 1979) (Figure 2). This method has been applied principally to evaluating the effects of various fertilizer treatments on the trees' overall nutrient status, but it can also be used



DIRECTION OF SHIFT	RESPONSE IN			CHANGE IN	
	NEEDLE WEIGHT	NUTRIENT		NUTRIENT STATUS	POSSIBLE DIAGNOSIS
		CONC.	CONTENT		
A	+	−	+	DILUTION	NON-LIMITING
B	+	0	+	UNCHANGED	NON-LIMITING
C	+	+	+	DEFICIENCY	LIMITING
D	0	+	+	LUXURY CONSUMPTION	NON-TOXIC
E	−	++	±	EXCESS	TOXIC
F	−	−	−	EXCESS	ANTAGONISTIC

FIGURE 2. Schematic relationships between nutrient concentration, nutrient content and dry weight of needles following fertilization (from Morrow (1979)).

for developing hypotheses about nutritional effects of other site or stand treatments. Inferences about nutrient uptake, growth dilution, luxury consumption, and possible induced deficiencies can be made by examining the amount and direction of change between the plotted points representing the control and treatments.

A third method of examining foliar nutrient data is using critical and optimum nutrient ratios. Some ratios of one nutrient to another are known to be quite useful; some need further study. A few important ratios are tentatively suggested in the following section and are included in the computerized diagnostic program presented in Section 3.

2.6.3 Some interpretive values for nutrient concentrations and ratios currently applied to coniferous species in British Columbia

This section suggests some interpretations of foliar nutrient levels in several conifer species occurring in British Columbia. These interpretations are subject to the considerations discussed in the preceding section. Many of the interpretations are consistent with those reported in the review by Morrison (1974). In most cases, the existence and severity of deficiencies have been inferred from the relative magnitude of response when a nutrient was applied. Data are reported in various ways in the original literature. Consequently, estimates have had to be made in some cases, where the threshold presumably lies between the particular categories (e.g., "severely" and "moderately" deficient) which have been adopted.

Table 4 suggests interpretations of macronutrient concentrations in several species. Data for N, P, and K in most of these species are derived partly from the work of Everard (1973), who dealt with plantations beyond the seedling stage. Douglas-fir interpretations are also based partly on data of Heilman (1971), Heilman and Ekuan (1973), and Turner (1966), and on ranges reported by Gessel et al. (1960). Lodgepole pine and white spruce interpretations are based partly on data of Swan (1972 and 1971, respectively). Western hemlock interpretations are based partly on information of Heilman and Ekuan (1973) and van den Driessche (1976). Western redcedar interpretations are based on greenhouse seedling data of Walker et al. (1955).

Nutritional interpretations have not yet been developed for all nutrients in all conifer species of interest. However, available data suggest some similarities among different genera within the Pinaceae. Tables 5, 6, and 7 present examples of interpretations which might apply widely, if not precisely.

Table 5 summarizes micronutrient interpretations which would tentatively apply broadly among the Pinaceae, in the absence of more specific information. Manganese data are based on work with Norway spruce by Ingestad (1958) and Zech (1970b). Zinc interpretations are based on data

TABLE 4. Interpretations of foliar macronutrient concentrations

Element	Interpretation	Foliar Concentration (percent, dry mass basis)				
		Douglas-fir	Lodgepole pine	Western hemlock	White spruce	Western redcedar
N		0.00	0.00	0.00	0.00	0.00
	Very severely deficient					
		1.05	1.05	0.95	1.05	1.15
	Severely deficient					
		1.30	1.20	1.20	1.30	1.50
	Slight moderate deficiency					
		1.45	1.55	1.45	1.55	1.65
	Adequate					
P		0.00	0.00	0.00	0.00	0.00
	Severely deficient					
		0.08	0.09	0.11	0.10	0.10
	Moderately deficient					
		0.10	0.12	0.15	0.14	0.13
	Slightly deficient					
		0.15	0.15	0.35	0.16	0.16
	Adequate					
K		0.00	0.00	0.00	0.00	0.00
	Very severely deficient					
		0.35	0.35	0.40	0.25	0.35
	Moderate-severe deficiency					
		0.45	0.40	0.45	0.30	0.40
	Slightly-moderately deficient					
		0.75	0.50	0.75	0.45	0.80
	Possibly slightly deficient					
		0.80	0.55	0.80	0.50	0.85
Ca		0.00	0.00	0.00	0.00	0.00
	Severely deficient					
		0.10	0.05	0.05	0.07	0.07
	Moderate-severely deficient					
		0.15	0.06	0.06	0.10	0.10
	Possible slight-moderate deficiency					
		0.20	0.08	0.08	0.15	0.20
	Little, if any deficiency					
		0.25	0.10	0.10	0.20	0.25
	No deficiency					
Mg		0.00	0.00	0.00	0.00	0.00
	Severely deficient					
		0.06	0.06	0.06	0.05	0.05
	Moderate-severely deficient					
		0.08	0.07	0.07	0.06	0.06
	Possible slight-moderate deficiency					
		0.10	0.09	0.09	0.10	0.12
	Little, if any deficiency					
		0.12	0.10	0.10	0.12	0.14
	No deficiency					

TABLE 5. Interpretations of foliar micronutrient concentrations[a]

Element	Foliar concentrations (ppm, dry mass basis)	Interpretation
Mn	0	Severe deficiency
	4	Probable deficiency
	15	Possible deficiency or near-deficiency
	25	No deficiency
Fe	0	Deficiency likely
	25	Possible deficiency
	50	Low to zero probability of deficiency
Active Fe	0	Deficiency likely
	30	Deficiency unlikely
Zn	0	Probable deficiency
	10	Possible deficiency
	15	No deficiency
Cu	0	Probable deficiency
	1	Possible moderate deficiency
	2	Possibly somewhat deficient
	2.6	Slight possibility of deficiency
	4	No deficiency
B	0	Deficiency likely
	10	B Possibly deficient; Possible NID[b]
	15	B Probably not deficient; If N<1.5, then NID[b] possible If N>1.5, than NID[b] unlikely
	30	No deficiency
Mo	0	May be deficient
	0.1	Not deficient

[a] These interpretations are not yet species-specific.

[b] N = N concentration, in percent; NID = deficiency inducible by nitrogen fertilizer application.

TABLE 6. Interpretations of element concentration ratios

Ratio	Threshold value	Interpretation
N/P	0.0 - - - - - - - - -	No P deficiency; NID[a] unlikely
	$6.111N^{b} + 0.11$ - - - -	No P deficiency; NID possible
	12.5 - - - - - - - - -	Possible P deficiency; NID or NAD[a] possible
	16.0 - - - - - - - - -	P deficiency
P/Al	0.0 - - - - - - - - -	P/Al suggests P deficiency, unless P > 0.13%
	3.0 - - - - - - - - -	(No interpretation)
K/Ca	0.0 - - - - - - - - -	Possible K deficiency
	0.5 - - - - - - - - -	(No interpretation)
	3.5 - - - - - - - - -	High K/Ca suggests desirability of checking for possible Fe deficiency
Ca/Mg	0.0 - - - - - - - - -	Ca/Mg is unusually low and may impair growth. If soil parent material is of ultramafic origin, consider possibilities of Mo deficiency and Ni and/or Cr toxicity.
	0.8 - - - - - - - - -	(No interpretation)

[a] NID = Deficiency inducible by N fertilization; NAD = deficiency may be aggravated by N fertilization.

[b] N = N percent, dry mass basis.

TABLE 7. Interpretations pertaining to foliar sulphur

S	0.00% - - - - - - -	If sulfate-S is not evaluated: data suggest actual or inducible S deficiency. If sulfate-S <.01% ppm, possible S deficiency and possible NAD[a]. If sulfate-S >.01% ppm, no S deficiency but NID[a] possible.
	0.12% - - - - - - -	Possible S deficiency and If sulfate-S <.01% ppm, NID[a] possible. If sulfate-S >.01% ppm, NID unlikely.
	0.14% - - - - - - -	S deficiency and NID are both unlikely.
	0.16% - - - - - - -	No S deficiency; NID unlikely.
N/S	(Not interpreted where total S exceeds 0.14%)	
	0 - - - - - - - - -	No S deficiency; NID unlikely.
	4.2N + 4.94[b] - - -	No S deficiency; NID possible.
	13.6 - - - - - - -	Possible S deficiency.
	14.6 - - - - - - -	S deficiency.
Sulfate-S	(The following applies only where total S has not been evaluated)	
	0.000% - - - - - -	Actual or inducible S deficiency; NAD or NID likely.
	0.008% - - - - - -	No S deficiency; but NID possible.
	0.020% - - - - - -	No S deficiency; NID unlikely.
	0.040% - - - - - -	Very high; possibly N deficient.

[a] NID = deficiency inducible by N fertilization; NAD = deficiency may be aggravated by N fertilization.

[b] N = N concentration, in percent.

for several species, reviewed by Stone (1968). Work by Zech (1968, 1970a, 1970b) with Norway spruce and Scots pine suggests approximate interpretations of total foliar Fe and more precise interpretation of the active Fe fraction; data of Majid (1984) tend to confirm the approximate threshold value for active Fe suggested by Zech's data. Copper interpretations are based on Douglas-fir data of Oldenkamp and Smilde (1966), lodgepole pine data of Majid (1984), Sitka spruce data of Benzian and Warren (1956), and Scots pine data of Wehrmann (1961). Boron interpretations are based on data of Vail et al. (1961) and Stone and Will (1965) for various pines; data for several species, reviewed by Stone (1968); lodgepole pine data of Braekke (1979) and Majid (1984); and observations of Carter et al. (1984) in Douglas-fir. Tentative molybdenum interpretation is based wholly on Mortvedt et al. (1971).

Tentative interpretations of several nutrient ratios are indicated in Table 6. Interpretations of N/P ratio are based on work by Ingestad (1963, 1966) and the review by van den Driessche (1974), pertaining to several species. One can visualize that a low N/P ratio signifies no P deficiency, i.e., N more limiting than P. If foliar N and N/P are low, N fertilizer application would tend to relieve the N deficiency and might lead to P limitation ("induced deficiency" of P). The same N/P ratio presumably has a somewhat different meaning, however, if foliar N concentration is higher; in this case, P supply is not only non-limiting before fertilization, but may remain adequate even after N fertilization. To take this into account, the interpretation (from N/P ratio) that P deficiency might be induced, makes use of a linear function of foliar N concentration (expressed in percent). It should be noted that hemlock appears especially susceptible to induction of P deficiency as a result of N fertilization, presumably because of detrimental effects on mycorrhizal short roots (Gill and Lavender 1983). Consequently, the N/P relationships of Table 6 might underestimate this problem for hemlock. Interpretation of P/Al ratio is suggested by work of Humphreys and Truman (1964) and Gentle (1970) with radiata pine in Australia; it remains to be determined whether the relationship is a general one, applicable to several species and conditions. We have not seen P/Al ratios in British Columbia conifers approach the critical level suggested by the work of Humphreys and Truman. Calcium/-magnesium ratio interpretations are based on data and discussion by Walker (1954), Kruckeberg (1969a), and Lavender (1970). The interpretation of low K/Ca ratios is from Norway spruce nursery data of Björkman (1953); the not uncommon association of Fe deficiency with very high ratios of K/Ca is described by de Kock (1963), and some data relevant to the relationship in Scots pine are presented by Zech (1970b). Data obtained by Majid (1984) and unpublished data of Ballard[1] for lodgepole pine indicate that the

[1] Ballard, T.M. 1979. Development of interim operational guidelines for forest fertilization in the Kamloops Forest District. Fac. Forestry, Univ. of B.C., Vancouver, B.C. 86p.

association of Fe deficiency with high K/Ca is not diagnostically reliable, but where only macronutrient analysis has been done, a high K/Ca ratio would suggest the desirability of directly evaluating foliar Fe.

Interpretations of S, N/S, and sulfate-S (Table 7) have been based on data of Kelly and Lambert (1972) for radiata pine and Turner et al. (1977) for Douglas-fir, and on general discussion by Dijkshoorn and van Wijk (1967) of N/S ratios in several plant data. The work by Turner et al. strongly suggests that S deficiency may be induced by N fertilizer application. A linear function of foliar N concentration (expressed in percent), for interpretation of N/S ratio, was originally based on foliar analysis data and responses to N and/or S observed by Heilman (1971) in Douglas-fir (Ballard 1979[1]). Subsequent observations of pre- and post-fertilization foliar N/S ratios in some British Columbia N fertilizer trials appear to confirm the usefulness of the relationship (Ballard 1982[2].

2.7 Soil Analysis and Interpretation

This section outlines some of the more common soil analytical techniques that can be used to identify possible causes of nutrient deficiencies detected by foliar analysis. As stated in Section 2.1, interpretations of the many methods for determining soil nutrient availability and its relationship to tree nutrient status have met with limited success. Therefore, no attempt has been made to offer an explicit listing of critical and/or optimum soil nutrient levels. Instead, levels felt to be of some use are cautiously suggested for several different analytical methods. Soil conditions likely to contribute to various nutrient deficiencies are also outlined. These guidelines must be used with care, as much of the information has been extrapolated from soils of different parent materials under different climates for a large number of species and are, therefore, not necessarily applicable to coniferous species of the Pacific Northwest.

As already discussed, soil analysis may be of less value for diagnosing the existence and severity of a nutritional problem than for inferring the reasons for a deficiency. One must weigh the potential value of soil analysis in every case before deciding whether the costs of sampling and/or analysis can be justified.

[1] Ballard, T.M. 1979. Development of interim operational guidelines for forest fertilization in the Kamloops Forest District. Fac. Forestry, Univ. of B.C., Vancouver, B.C. 86p.

[2] Ballard, T.M. 1982. Foliar analysis research. Fac. Forestry, Univ. of B.C., Vancouver, B.C. 19 p., 13 appendices.

While the potential value of the analysis is summarily described in this section, a supplementary review of recent literature would be worthwhile if one is contemplating much soil analysis. It will be seen in this section that field soil description (including drainage class, texture, pH, and parent material identification) greatly enhances interpretation of many chemical analyses, and nearly obviates some others.

2.7.1 Nitrogen

Nitrogen is the most commonly deficient nutrient in the Pacific Northwest. Most of the nitrogen in a soil is found in the organic matter. Significant amounts are not directly available to most trees, though some is indirectly available via mycorrhizal fungi. Most forest soils contain ammonium (as an exchangeable ion and in some cases fixed between clay micelles) and some also contain nitrate, the presence and abundance of which are sometimes indicators of relatively good nitrogen status. A principal source of available nitrogen for trees is that which has been mineralized to ammonium by fungi, bacteria, and soil animals. This ammonium can be oxidized to nitrate, another form of nitrogen available for uptake by most trees.

Nitrogen deficiencies often occur on sites that have very little organic matter, for example, as a result of past management practices in which surficial organic matter was removed through burning or scalping. However, the principal cause of nitrogen deficiency is usually low rates of mineralization. This can be due to many factors: Soil pH may be too low for many soil animals and microorganisms, with most decomposition being carried out by slowly metabolizing fungi. Soil temperature may be too low, aeration inadequate, or soil moisture either too wet or too dry. Forest floors and mineral soils in this situation normally have wide C:N ratios (i.e., greater than approximately 35-40 for forest floors and greater than approximately 18-20 for mineral soils other than Ah horizons) and mor humus forms.

Therefore the most useful tests for determining the cause(s) of nitrogen deficiency are likely: the determination of total nitrogen and total organic carbon to allow calculation of the C:N ratio; and the determination of mineralizable nitrogen. Mineralizable nitrogen gives an index of soil nitrogen that can easily be converted to available forms by microorganisms over time. A number of studies have shown good relationships between mineralizable N and foliar N concentration; response to N fertilization; nitrogen uptake; and site index (e.g., Zötti 1960; Le Tacon 1972; Shumway and Atkinson 1978; Powers 1980). A commonly used procedure for the determination of mineralizable N involves anaerobic incubation at 30°C for two weeks (Waring and Bremner 1964).

Optimal or threshold values for mineralizable N have not been established for different species, site types and stocking levels. In general, as mineralizable N levels become lower, the nitrogen supplying power of the soil declines. Shumway and Atkinson (1978) suggested that response of Douglas-fir to nitrogen applications is high when mineralizable N <25 ppm, moderate between 26 and 50 ppm, and low at levels > 50 ppm. Powers (1980) found similar trends in Pinus ponderosa L., with soils testing less than 12 ppm of mineralizable N judged as clearly deficient, and stands with up to 16 ppm N still showing a response to N fertilization. However, he measured total ammonium N rather than just the N mineralized during incubation (i.e., he did not subtract the extractable ammonium present before incubation).

2.7.2 Phosphorus

Phosphorus nutrition and the chemistry of soil phosphorus are complex. Although phosphorus available for uptake is found in the soil solution, of most soils the soluble phosphate represents only a very small fraction of the total P. This fraction is especially small if soil pH is less than 5.0 or more than 6.5. The remaining phosphates are found in the organic matter and as insoluble inorganic phosphates. Some inorganic phosphates are released into the soil solution during decomposition of organic matter, but most are quickly converted into unavailable organic phosphates. Some of the available phosphates in the soil solution come from this inorganic pool. The P concentration of the soil solution and the ability of a soil to buffer against changes in this concentration are important parameters controlling the phosphate supply to plant roots.

Identification of phosphorus-deficient sites through soil analysis is very difficult. Of the many extraction procedures currently in use, the most common are the Bray No. 1 and Bray No. 2. (Bray and Kurtz 1945). The difficulties associated with use of these methods arise because phosphorus nutrition is dependent on several factors outside of phosphate availability. The kind and vigour of mycorrhizal populations associated with the roots can affect both uptake and availability. Soil nitrogen concentration can effect mycorrhizal development, and the soil's ability to maintain soil solution phosphate concentrations during periods of high demand can also affect phosphorus nutrition.

The choice of the most suitable soil horizon(s) or layers for analysis also presents problems. Podzolic B horizons, common throughout much of British Columbia, will normally have very low extractable P, while forest floor materials will generally have much higher levels. Therefore, depending on the spatial distribution of the phosphate-absorbing roots, phosphate availability can vary considerably within a soil profile.

In general, if extractable P is high (rare in forested mineral soils of British Columbia) it is unlikely that the availability of soil P is the cause of any P deficiencies observed through foliar analysis. If extractable P is low (< 2 ppm extractable P) it is difficult for precise interpretations to be made without more knowledge of the factors controlling availability and uptake for each tree species over a range of soils and sites.

2.7.3 Sulphur

The sulphur requirements of trees can be met by the supply in the soil, atmospheric inputs, and/or fertilizer applications. The S available to trees is the sulphate-S (SO_4^{-2}) found in the soil solution and the sulphate-S adsorbed on soil colloids. This sulphate-S usually represents a fraction of the soil's total S. The principal reservoir of S in soils is that which is contained in the soil organic matter, although some rocks and parent materials contain significant supplies of sulphates and sulphides that can be released as sulphate through weathering. In general, the greater the amount of soil organic matter, the greater the amount of soil S.

This organic S fraction of the soil is made available to plants by microbial activity under aerobic conditions, an activity that is greatest when soils are warm and moist with an adequate nitrogen supply.

Uptake and use of sulphate-S is not significantly affected by soil pH or other nutrients (except selenium, which will depress sulphate uptake when in high concentrations). Sulphur must, however, be in sufficient supply to allow for the use of other nutrients, nitrogen in particular, since it is an essential constituent of proteins.

Several methods have been used to evaluate the sulphur-supplying power of a soil. Water-soluble plus adsorbed-sulphate in the root zone indicates a soil's immediate ability to supply sulphate sulphur, while total sulphur and, occasionally, mineralizable sulphur are an index of a soil's sulphur reserves and long term ability to supply sulphur. Water-soluble plus adsorbed-sulphate can be determined by using the method of Johnson and Nishita (1952), while mineralizable S can be determined by the procedure used by Radwan and Shumway (1983). Levels of total and sulphate sulphur associated with normal and deficient foliage status have not yet been established for forest soils of British Columbia. Difficulties arise when it has to be decided which mineral soil horizon or forest floor layer is most useful in evaluating sulphate availability to the tree.

The ratio of total C to N and S in soil organic matter has been recorded for many surface soils (Williams 1975) and usually falls in the range of 140:10:1.3 to 300:14:1 (Turner 1979). It may be possible to use these ratios to estimate the relative amounts of N and S released during

organic matter mineralization. If the soil N:S ratio is high (i.e., >12) sulphur supplies will have to be made up from the soil inorganic S reserves or from aerosol and precipitation inputs; otherwise, S may be deficient.

2.7.4 Potassium and magnesium

An excellent review of K, Mg, and S deficiencies in forest trees has been written by Leaf (1968). Potassium and Mg are discussed together because the soil conditions related to each deficiency are quite similar: acid, sandy to loamy sand soils, low organic matter content, and low total cation exchange capacity and base saturation. He suggested that soils of alluvial, glacio-fluvial, and blown sand origins are more likely to show Mg and K deficiencies than are soils of glacial till origin.

The balance of the exchangeable cations K, Mg, and Ca appears to be very important. Calcium and Mg both compete for the same carrier site and excesses of one may induce or aggravate deficiencies of another. The exchangeable Ca:Mg ratio is often examined and normally ranges from approximately 3:1 to 5:1, although values outside of this range do not necessarily mean a deficiency exists.

Several analytical methods have been examined to develop "available to trees" fractions of Mg and K. As an approximate guide, soils testing less than 10-12 ppm extractable Mg (neutral 1N NH_4OAc) and less than 15 ppm exchangeable K (NH_4OAc, NH_4NO_3, and weak HCl-extractable) may be Mg or K deficient. Leaf (1968) proposed that a better method may be the use of 0.5N HNO_2 with 10-minute boiling, as this method separates Mg-deficient from possibly K-deficient soils (or visa versa) more adequately. The "critical levels" he suggested with this procedure are 140-150 ppm extractable Mg and 50-60 ppm extractable K.

2.7.5 Calcium

Calcium is important not only in its role as a tree nutrient, but also for its role in soil improvement. It counteracts acidification and is important in determining soil structure. Critical levels of exchangeable or extractable calcium are not normally used as a measure of calcium deficiency because Ca deficiencies are rare in conifers. Instead, soil Ca or "lime" requirements are normally related to pH. Soil pH affects nutrient availability, the solubility of toxic substances (such as Al), soil microorganisms, and root development.

Forest soils developed from acid igneous parent materials such as quartz- and granodiorites are quite common in the Pacific Northwest. These soils are relatively acid and coarse-textured, and are generally poorly supplied with Ca, Mg, and K. These conditions, combined with soil pH less

than approximately 2.8 (0.01 M $CaCl_2$), might describe forest soils most likely to be Ca deficient. However, native conifers appear to be able to extract an adequate amount of Ca, even when exchangeable Ca falls as low as 0.001%. This applies in particular to deep-rooted trees which establish a balance by permeating a larger volume of soil (Baule and Fricker 1970).

2.7.6 Boron, copper, and zinc

Suspected deficiencies of these micronutrients are currently under study in southwestern British Columbia (Klinka and Carter 1983). Many of the soil and site conditions controlling the supply and availability of these micronutrients are quite similar. In general, deficiencies of B, Cu, and Zn most commonly occur on coarse-textured (sands and loamy sands) soils of igneous origin. These soils are often low in organic matter and have commonly been water-worked: alluvial, fluvial, and glacio-fluvial, for example. Acid organic peats and mucks also appear to have low levels of total and/or available B, Cu, and Zn. Soils that have experienced losses of organic matter and/or surface mineral horizons through burning, scalping, or erosion may also be deficient in these micronutrients.

Boron deficiency is common in agricultural and orchard crops in the Pacific Northwest and widespread deficiencies are suspected in several forest species. Sites suspected of being boron deficient commonly have surplus soil moisture through most of the growing season, followed by a short but possibly severe period of summer moisture deficit. Soils near the ocean or under the influence of ocean spray or fog-belts, as well as soils originating from sedimentary or sea-bed materials, are unlikely to be deficient. Soils with high concentrations of available Ca, K, and N may aggravate or induce B deficiences.

Boron availability in soils is normally measured as hot-water extractable boron determined through the curcumin method (Dible et al. 1954; Spicer and Strickland 1958). Deficiency levels relating to forest soils of the Pacific Northwest have not been established, but values ranging from 0.15 to 0.6 ppm hot water extractable B have been suggested for other forest crops (Stone 1968).

Methods of assessing soil Cu status have not been satisfactorily established. Copper is firmly complexed or chelated in soil organic matter, and interactions between Cu and N, P, and Mo make it difficult to estimate the Cu available for uptake by trees.

Both inorganic and chelating extractants have been used to determine the amount of plant-available Cu. Mengel and Kirby (1982) suggested that a minimum of 4 ppm Cu extracted by 1N HNO_3 and 0.2 ppm Cu extracted by DTPA may represent critical soil levels for some agricultural crops. Critical

levels for forest crops have not been established. Soil and foliage P contents have been shown to have an inverse effect on foliage Cu content (Oldenkamp and Smilde 1966). Similarly, Cu deficiency can be aggravated or induced by high levels of available N when Cu supplies are low; a similar interaction between Cu and Mo has been postulated (Stone 1968).

No threshold values are suggested for soils likely to be deficient in zinc. In general, zinc deficiency appears to be most common on exposed subsoils and soils low in organic matter with little or no forest floor. Soils with pH 6 or greater may have limited Zn availability. High concentrations of available phosphates may also induce or aggravate possible Zn deficiencies.

2.7.7 Iron

Iron deficiencies are rarely due to insufficient soil Fe content, particularly in the relatively acid forest soils of the Pacific Northwest. Therefore, analyses of soil Fe content rarely provide an index of availability and/or deficiency. Iron deficiencies are most common on well-drained calcareous soils (pH 7.5 or greater) and excesses of phosphate may further aggravate Fe deficiencies on these calcareous soils. As well, Fe deficiencies may occur on some well-drained sandy soils at lower pH, but may be more common on soils that experience a summer drought. Several other interactions between Fe, Cu, Zn, Ca, and P have been investigated but are felt to be beyond the scope of this manual.

2.7.8 Manganese

Manganese deficiencies are extremely rare in forest soils, but there has been considerable interest in Mn toxicity. The factors controlling Mn availability are very similar to those controlling Fe availability, with both tending to parallel soil pH closely. On calcareous soils and other soils of neutral or alkaline pH, Mn availability is usually very low; in most acid forest soils it is generally high. Manganese deficiency, as with Fe deficiency, may be aggravated by long droughts, apparently because roots cannot exploit the more acid organic surface layers (Stone 1968).

3 COMPUTERIZED DIAGNOSTIC PROGRAMS

The program introduced in this chapter analyzes nutrient concentrations and compares them with the interpretations outlined in the previous chapter. It produces a one-page report that lists relevant stand information and diagnoses either single tree or stand nutrient status. Program users must understand the limitations of using foliar data expressed as concentrations and the limitations of foliar analysis in general. The interpretations made by this program are tentative, because some nutritional problems in some species have received little research attention, and other nutritional problems enable only imprecise interpretations.

The MBASIC version of the forest nutrient analysis program "FNA" has been written by John Emanuel, University of British Columbia (U.B.C.), Faculty of Forestry, and is based on an earlier program by Ballard (1982). This program is also available on the U.B.C. "General" system. The program is listed under F203:FNA with the documentation listed under F203:FNA.W. These files have been made accessible to all U.B.C. users.

3.1 How to Use

At present, FNA is designed for use with the IBM, Kaypro, and Osborne 1 personal computers using single- or double-density disk drives and dot matrix printer. It can be easily adapted to other computer/printer combinations.

To run the program, switch the system on, place the diskette in drive "a", and press RETURN. MBASIC is automatically loaded into memory. At this point, type:

```
run "fna"
```

and press the RETURN button. You will be prompted for the information listed in the next section.

NOTE: Do not remove the program diskette from drive "a" until the program has stopped. A data base is accessed repeatedly during execution.

3.2 Input Data

3.2.1 The input routine

The program is fully interactive, and has some special features built into the keyboard input routine. These are listed below:

-- The prompt character is an "=". It appears to the left of the cursor at the field being prompted.

-- You can skip almost any field by pressing RETURN.

-- The TAB button does the opposite of the RETURN button. Any time it is pressed, the program backspaces one field, allowing you to change previously entered information. (On the IBM personal computer this function is carried out by the ESC button.)

-- The ESC button causes the contents of the screen (up to column 75) to be printed. This function produced the sample screens in Section 3.5 of this writeup. Be careful to avoid pressing ESC by mistake.

-- The horizontal cursor buttons (left-arrow and right-arrow) are functional for input fields larger than one digit.

-- The vertical cursor buttons (up-arrow and down-arrow), and any other seemingly incorrect entries have no effect on the program.

-- Real values (the nutrient concentration values) can be entered in free-format, with an optional decimal point.

3.2.2 Information requested

The following information is requested by the program. Only three items are required by the program and are indicated below with an *. All other prompts can be skipped with the RETURN key.

-- * The species of tree from which the sample is taken. The program is currently capable of analyzing samples from five species:

1. coastal Douglas-fir (Pseudotsuga menziesii)
2. lodgepole pine (Pinus contorta)
3. western hemlock (Tsuga heterophylla)
4. white spruce (Picea glauca), and
5. western redcedar (Thuja plicata)

Enter a number from 1 to 5.

-- The sample year. This can be any two numbers.

-- * The sampling season. So far, all research has been directed towards dormant-season samples. If the growing season is used, all comments are suppressed in the output. Enter "d" (dormant) or "g" (growing) (D or G also work). To evaluate a growing season sample

without suppressing comments, you can enter d and make a note in the "Remarks" section.

-- * Which season's foliage. So far, all research has been directed towards samples from the current year's foliage. If only previous year's foliage data are available, levels of adequacy cannot be ascertained, and comments are suppressed on printout. Enter "c" (current), "p" (previous), or "b"(both) to indicate which season's foliage has been analyzed (C, P, or B are acceptable). If only previous year's foliage data are available and you would like a printout with comments and adequacy values, you can imitate current year's foliage by entering "c".

-- Your initials. Enter any two letters.

-- Sample number. Enter any two numbers.

-- Location description. Enter a description of the sample location (up to 62 characters long).

-- Latitude. Enter the latitude, in degrees and minutes, of the stand being analyzed.

-- Longitude. Enter the longitude, in degrees and minutes.

-- Elevation. Enter the elevation, in metres, of the stand being analyzed.

-- Biogeoclimatic unit. Enter symbol for a subzone or a variant.

-- Relative hygrotope class. The following potential hygrotope classes of the relative scale (Klinka et al. 1985) are recognized by the program:

0. very xeric
1. xeric
2. subxeric
3. submesic
4. mesic
5. subhygric
6. hygric
7. subhydric

Enter a number from 0 to 7, or press RETURN to skip.

-- Trophotope class. The following trophotope classes of the absolute scale (Klinka et al. 1985) are recognized by the program:

A. nutrient-very poor (oligotrophic)
B. nutrient-poor (submesotrophic)
C. nutrient-medium (mesotrophic)
D. nutrient-rich (permesotrophic)
E. nutrient-very rich (eutrophic)

Enter a letter from A to E (or "a" to "e") indicating relative trophotope, or press RETURN to skip.

-- Ecosystem or site association. Enter a description, up to 53 characters long, indicating the plant association.

-- Remarks. Enter two lines of up to 73 characters each, indicating any additional information about the stand being analyzed.

-- Number of trees in composite sample. Most samples consist of foliage from more than one tree, that has been combined to form a composite sample. Enter the number of trees that were sampled in this analysis. If individual trees were sampled, enter "1".

-- Nutrient concentration values. You are now prompted for concentration values for current and/or previous years' foliage. Enter values in % or ppm as indicated, or press RETURN to omit any element from the analysis. The following 15 nutrients are currently evaluated:

1. N (%)
2. P (%)
3. K (%)
4. Ca (%)
5. Mg (%)
6. S (%)
7. SO4-S (Sulfate-S) (%)
8. Al (%)
9. Mn (ppm)
10. Fe (ppm)
11. AFe (Active Iron) (ppm)
12. Zn (ppm)
13. Cu (ppm)
14. B (ppm)
15. Mo (ppm)

Each entry can be up to five digits long and can optionally contain a decimal point.

3.3 Program Output

The program output has three sections: headings, the body, and a listing of the ranked supply of nutrients.

The headings contain information read from the input data. The SAMPLE identification contains the sampling year; "d" or "g" indicating dormant or growing season; "c", "p", or "b", indicating the current, previous, or both years' foliage; your initials; and the sample number. The number and letter indicate relative hygrotope and trophotope respectively.

The body lists all non-missing nutrients and gives interpretations and comments. Comments are based only on current year's foliage. The initials "NID" indicate nitrogen fertilization may induce a deficiency in another nutrient. Similarly, "NAD" indicates that nitrogen fertilization may aggravate an apparent deficiency.

The list of nutrients in ranked order attempts to put nutrient values into perspective by ranking them according to their relative concentrations. It is only performed on current year's foliage collected during the dormant season. The concentration of each nutrient under evaluation is divided by the concentration of each of the other nutrients under evaluation. Simultaneously, each predefined adequate nutrient concentration is divided by the adequate concentration value for each of the other nutrients. Depending on which result is greater (actual or adequate), one is added to the rank of the numerator's, or of the denominator's. The nutrients are then listed from lowest to highest rank (most deficient to least deficient).

3.4 Associated Files

The program diskette contains five files associated with the foliar nutrient analysis program. These are described below:

-- fna.BAS is the main program file.

-- fnarem.BAS is an ASCII file containing remarks and a variable list for fna.BAS. To produce a listing of the program, first merge "fnarem" with "fna.BAS" and then issue the list (or "Llist" if you want a printout) command.

-- fnamaint.BAS is a program that maintains the data base, fnabase.dat. It is written in MBASIC, and is documented in the writeup, FNAMAINT.

-- copybase.BAS is a simple MBASIC program that copies the data base, fnabase.dat, from drive "a" to drive "b". When the program is run, it immediately starts copying.

3.5 Sample Input Screens and Output

The following figures (Figs. 3, 4, 5, and 6) depict the layout of the four input screens displayed during data input. They have been made using the ESC function during the last prompt of the screen. Note the "=" on the bottom of each screen, indicating the line being prompted. The subsequent program output uses the data presented in the sample screens.

```
                    FOLIAR NUTRIENT ANALYSIS

Ballard, T.M., Forest Soils
University of B.C.                          Edition 830215
   Amended by J.E. Emanuel and R.E. Carter

Which species do you wish to analyse?
   1  =  Coastal Douglas-fir
   2  =  Lodgepole Pine
   3  =  Western Hemlock
   4  =  White Spruce
   5  =  Western Red Cedar                   1
Enter sample year (i.e. 83)                 83
Which sampling season?
   D  =  Dormant
   G  =  Growing                            d
Which season's foliage?
   C  =  Current
   P  =  Previous
   B  =  Both                               b
Your initials (2 letters)                   JE
Sample number (2 digits)                    01
Stand age (3 digits)                        999
Location description (62 characters)
=          location desc. (62 characters)
```

FIGURE 3. The first input screen.

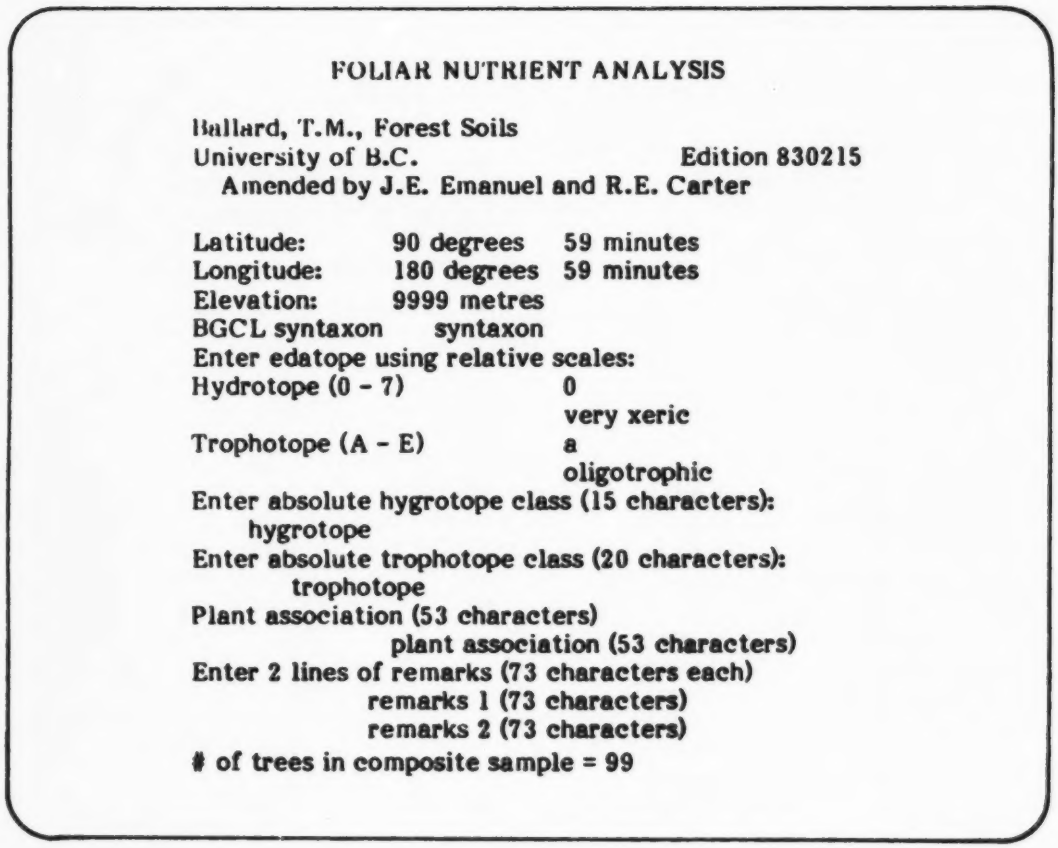

FOLIAR NUTRIENT ANALYSIS
Ballard, T.M., Forest Soils
University of B.C.
Edition 830215
Amended by J.E. Emanuel and R.E. Carter
Latitude: 90 degrees 59 minutes
Longitude: 180 degrees 59 minutes
Elevation: 9999 metres
BGCL syntaxon syntaxon
Enter edatope using relative scales:
Hydrotope (0 - 7) 0
very xeric
Trophotope (A - E) a
oligotrophic
Enter absolute hygrotope class (15 characters):
hygrotope
Enter absolute trophotope class (20 characters):
trophotope
Plant association (53 characters)
plant association (53 characters)
Enter 2 lines of remarks (73 characters each)
remarks 1 (73 characters)
remarks 2 (73 characters)
# of trees in composite sample = 99

FIGURE 4. The second input screen.

FOLIAR NUTRIENT ANALYSIS

Ballard, T.M., Forest Soils
University of B.C. Edition 830215
Amended by J.E. Emanuel and R.E. Carter

Enter nutrient concentration values

		CURRENT YEAR	PREVIOUS YEAR
N	(%)	1.9	2.0
P	(%)	.11	.12
K	(%)	.57	.58
Ca	(%)	.05	.06
Mg	(%)	.07	.08
S	(%)	.14	.15
S04-S	(%)	.01	.02
Al	(%)	.06	.07
Mn	(ppm)	25.	26.
Fe	(ppm)	47.	48.
AFe	(ppm)	29.	30.
Zn	(ppm)	11.2	11.3
Cu	(ppm)	1.5	1.6
B	(ppm)	13.	14.
Mo	(ppm)	.27	=.28

FIGURE 5. The third input screen.

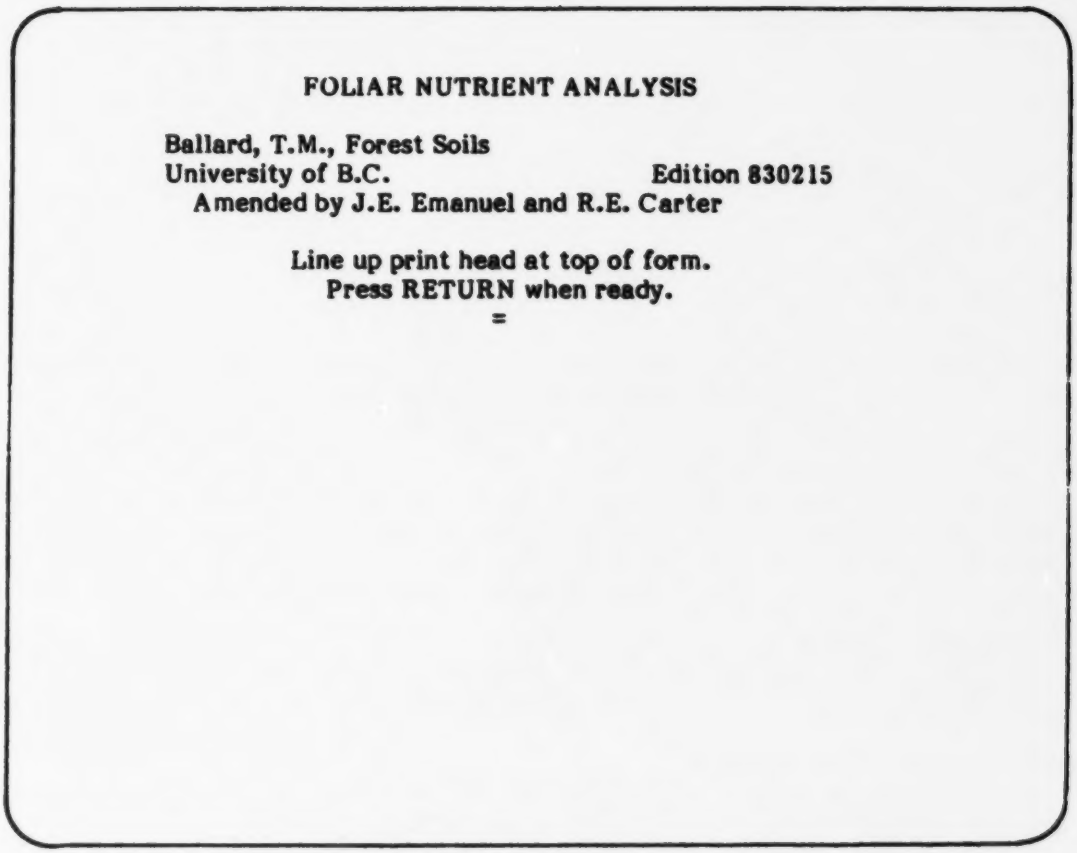

FOLIAR NUTRIENT ANALYSIS
Ballard, T.M., Forest Soils
University of B.C.
Edition 830215
Amended by J.E. Emanuel and R.E. Carter
Line up print head at top of form.
Press RETURN when ready.
=

FIGURE 6. The fourth input screen.

FOLIAR NUTRIENT ANALYSIS

SPECIES : Pseudotsuga menziesii — Coastal Douglas-fir
SAMPLE : 82BDRC04 — STAND AGE : 72 years

LOCATION : latitude: 47°54' longitude: 124°22' elevation: 145 metres
MAPLE GROVE - COWICHAN LAKE

BGCL SYNTAXON : CWHa2 — RELATIVE HYGROTOPE : F - M
ABSOLUTE TROPHOTOPE CLASS : nutrient - MED-RICH
PLANT ASSOCIATION : TIARELLA-POLYSTICHUM-F-Bg-C

Diagnosis is based on analysis of 15 trees.
This stand was used in the characterization of the most productive sites for the growth of Douglas-fir.

ELEMENT or RATIO	CURRENT YEAR % or PPM	% DEV / ADEQUATE	PREVIOUS % or PPM	COMMENTS
Macronutrient status (%) :				
N	1.480	10	1.530	Adequate
P	0.179	19	0.182	Adequate
K	0.637	-2	0.594	Little if any deficiency
Ca	0.385	54	0.426	Adequate
Mg	0.157	43	0.160	Adequate
Element concentration ratios :				
N/P	8.268		8.407	No P deficiency; NID is unlikely
P/Al	13.769		10.706	(No interpretation)
K/Ca	1.655		1.394	(No interpretation)
Ca/Mg	2.452		2.662	(No interpretation)
Sulfur analysis (%) :				
S	0.123	-23	0.125	Possible S deficiency; NID unlikely
N/S	12.033		12.240	No S deficiency but NID possible
Micronutrient status (ppm) :				
Fe	53.000	18	59.000	No deficiency
AFe	30.000	0	34.000	Deficiency likely
Mn	225.000	800	239.000	No deficiency
Zn	15.000	25	16.100	Slight possibility of deficiency
Cu	3.000	15	3.000	Slight possibility of deficiency
B	10.500	-13	11.400	B possibly deficient; possible NID

Supply of nutrients in ranked order :

S ≤ B ≤ K ≤ AFe ≤ N ≤ Cu ≤ Fe ≤ P ≤ Zn ≤ Mg ≤ Ca ≤ Mn

FIGURE 7. FNA output.

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